BAYESIAN APPROACH TO ^{14}C DATES FOR ESTIMATION OF LONG-TERM ARCHAEOLOGICAL SEQUENCES IN ARID ENVIRONMENTS: THE HOLOCENE SITE OF TAKARKORI ROCKSHELTER, SOUTHWEST LIBYA

Alexander Cherkinsky

Center for Applied Isotope Studies, University of Georgia, 120 Riverbend Road, Athens, Georgia, USA. Corresponding author. Email: acherkin@uga.edu.

Savino di Lernia

Dipartimento di Scienze dell'Antichità Sapienza, Università di Roma, Via dei Volsci 122, 00185 Rome, Italy. School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, PB 3, Johannesburg 2050, South Africa.

ABSTRACT. Caves and rockshelters are critical loci for the analysis and understanding of human trajectories in the past. Use and re-uses of the same context, however, might have had serious impacts on depositional aspects. This is particularly true for the archaeological history of desert environments, such as the central Sahara, where most of the deposits are made of loose sand, rich in organic matter. Besides traditional stratigraphic reconstructions and a detailed study of the material culture, radiocarbon measurements from different contexts analyzing several types of material (bone, dried and charred coprolite, uncharred and charred plant remains, etc.) can highlight intrinsic critical aspects of ^{14}C determinations. These measurements must be carefully evaluated to provide a correct chronological assessment of the life history of the site. We present the statistics derived from the set of about 50 ^{14}C measurements from the site of Takarkori, southwest Libya, where early Holocene foragers and then groups of cattle herders inhabited the area from ~10,200 to 4600 cal yr BP. We have used the BCal Bayesian ^{14}C calibration program designed for statistical presentation of the calibrated data and the estimation of their probability for different phases. Results indicate that the Takarkori rockshelter was occupied during 4 phases of the following cultures: Late Acacus from 10,170 to 8180 cal yr BP; Early Pastoral, 8180–6890 cal yr BP; Middle Pastoral, 7160–5610 cal yr BP; and Late Pastoral, 5700–4650 cal yr BP.

INTRODUCTION

Bayesian statistical tools are now routinely used by archaeologists who wish to formally and coherently incorporate *a priori* knowledge, a formal model, and suitable data to arrive at (*a posteriori*) inferences that are based on all three. Initially, attention was focused on the calibration and interpretation of radiocarbon data. However, it soon became clear that the framework was ideally suited for the integration of chronological information from a range of different sources—in particular, stratigraphic sequences and historical or absolute evidence (Buck et al. 1991; Litton and Buck 1995). It is possible to devise a Bayesian version of traditional serial models, thus allowing *a priori* relative chronological information to be incorporated into the data interpretation process (Buck 2004).

The existing Bayesian chronology-building packages OxCal (Bronk Ramsey 1995) and Bcal (Buck et al. 1999) are widely used by archaeologists. They allow users to build sophisticated chronologies by tying together information such as chronometric dates, *a priori* information about absolute dates, stratigraphic sequences, archaeological phases, and interrelated phases and sequences.

It is important that the Bayesian calibration does not test the model in any meaningful sense. Rather, this calibration takes the model as a given set of facts and data back to the best estimates of model parameters—the ages of archaeological events of interest for the model. The Bayesian paradigm could be used to experiment with the few different ways in which we model or represent our prior information to see how such changes will alter the interferences we make.

The method of combining ^{14}C dates and other information is based on the appropriate definition of probability *a priori* $P(T)$. In most cases, we know nothing or very a little about the age of the sample before measurement and we should assume the probability *a priori* as approximately constant. This

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assumption is a basic one for calculating the calendar age with calibration programs. However, often we have some information that refers to the age of dated samples before measurement, such as dating climatic changes and environmental variations or stratigraphic data.

A Bayesian approach makes inferences based on the *a posteriori* probability distributions of the parameters. In the Bayesian approach, all forms of uncertainty are expressed in terms of probability, and facts that are established prior to the collection of new data are held to be essential in their understanding. The Bayesian theorem refers to conditional likelihood. This theorem regarding to ^{14}C and calendar ages may be expressed by Equation 1:

$$P(T/D) = P(D/T) \times P(T) \times C \quad (1)$$

where $P(T/D)$ is the probability that the calendar age of the sample is equal to T on the condition that the measured ^{14}C age has value D; $P(D/T)$ is the probability that the measured ^{14}C age is equal to D on the condition that the calendar age has value T; $P(T)$ is the probability *a priori* that the calendar age of the sample equals T, which incorporates our knowledge about the age before ^{14}C dating; C is a normalization constant.

The probability $P(D/T)$ could be defined as a Gaussian probability distribution. The distribution of probability over possible values of data is formally expressed as a probability density function (PDF). This is a mathematical function such that, if it is plotted on a graph, the area between the curve and the x axis is the area under the curve representing probability. The probabilities are recorded on the scale from 0 to 1, and when all probabilities are taken into account their probabilities must always add up to 1. The likelihood function is the form taken by a particular probability density function. The likelihood describes the probability of obtaining a particular set of data, given the probability models we have selected to represent the phenomena under study and the specific values of their parameters.

The method of combining ^{14}C dates and other information is based on the appropriate definition of probability *a priori* $P(T)$. In several cases, we know very little or nothing about the age of the samples before analysis, and should assume the probability as an approximate value. This assumption is the basis for the calculation of the calendar age with a calibration program. However, there are cases where we have prior information that relates to the age of the samples before analysis, for instance: stratigraphic data; results of dating by other methods; or even some historical dates. If we express these data by a mean probability distribution, the Bayesian approach allows their inclusion in the calculation of the probability distribution of calendar age. This procedure enables us to obtain a more precise calendar age of the sample because it takes into consideration both the ^{14}C age and data from other sources.

The incorporation of chronological information such as stratigraphic data complicates the calculation, and it should be done only when there is a sequence of ^{14}C dates. It must also include information about the chronological order of these dates.

MATERIALS AND METHODS

We have applied a Bayesian approach to determine the time intervals of 4 phases (Table 1) of human occupation at Takarkori rockshelter (Table 1) and to analyze the character of transitions for the different cultural stages of these phases. We used the software developed by Buck et al. (1999) at Sheffield University (http://bcal.sheffield.ac.uk).

Table 1 Radiocarbon ages of the 4 cultural phases of Takarkori rockshelter. Calibration intervals were calculated using the CALIB 6.0 program (Reimer et al. 2009).

Lab nr	Material	Age	Calibrated yr BC (95% confidence)	Calibrated yr BP (95% confidence)
Late Pastoral				
LTL670A	Human bone	4291 ± 50	3090–2700	5040–4650
GX-31071	Skin (sheep/goat)	4590 ± 80	3630–3030	5580–4970
GX-30325	Dung	4800 ± 70	3710–3370	5660–5320
LTL908A	Coprolite	4841 ± 50	3750–3510	5700–5460
Middle Pastoral				
UGAMS#8707	Seeds	4970 ± 25	3800–3660	5750–5610
LTL907A	Charcoal	5064 ± 55	3970–3710	5920–5660
LTL362A	Skin (sheep/goat)	5070 ± 35	3960–3780	5910–5730
UGAMS#10149	Dung	5170 ± 25	4003–3951	5990–5900
UGAMS#01843	Collagen	5280 ± 50	4240–3980	6190–5920
UGAMS#01841	Collagen	5340 ± 50	4330–4040	6280–5990
GX-31077	Bone collagen	5600 ± 70	4600–4330	6550–6280
LTL367A	Dung	5980 ± 50	5000–4720	6950–6670
UGAMS#2852	Enamel bioapatite	5980 ± 70	5050–4710	7000–6660
GX-30324-AMS	Human bone	6090 ± 60	5210–4840	7160–6790
Early Pastoral				
UGAMS#01842[a]	Collagen	6230 ± 90	5470–4940	7420–6890
GX-31074-AMS	Human bone	6540 ± 70	5630–5370	7570–7310
GX-31073-AMS	Human bone	6740 ± 70	5760–5520	7710–7470
LTL1585A	Human bone	6763 ± 55	5750–5560	7700–7510
GX-31075-AMS	Human bone	6900 ± 70	5980–5660	7930–7610
LTL911A	Human bone	7068 ± 100	6210–5730	8160–7670
GX-30326	Dung	7070 ± 100	6210–5730	8160–7680
GX-31064	Soil	7130 ± 100	6230–5800	8180–7750
GX-31076-AMS	Human bone	7130 ± 70	6210–5840	8160–7790
LTL1586A	Human bone	7155 ± 65	6210–5890	8160–7840
LTL914A	Human bone	7327 ± 65	6370–6060	8320–8000
Late Acacus				
GX-31066	Soil	7470 ± 100	6490–6080	8440–8030
GX-31069	Soil	7580 ± 110	6650–6230	8590–8180
LTL369A	Charcoal	7694 ± 60	6640–6440	8590–8390
GX-31070	Charcoal	7730 ± 100	7010–6390	8950–8340
LTL364A	Charcoal	7801 ± 35	6700–6510	8650–8450
LTL365A	Dung	7820 ± 50	6820–6500	8770–8450
GX-31068	Soil	7890 ± 110	7060–6500	9010–8450
UGAMS#10148	Seeds	7910 ± 30	6842–6653	8800–8600
UGAMS#8708	Seeds	7930 ± 30	7030–6680	8980–8630
LTL910A	Human bone	7973 ± 45	7050–6690	9000–8640
LTL368A	Charcoal	8031 ± 65	7140–6690	9090–8640
GX-31065	Soil	8040 ± 110	7310–6650	9260–8600
LTL366A	Charcoal	8049 ± 40	7140–6820	9080–8770
GX-31067	Soil	8080 ± 110	7360–6670	9310–8620
GX-31072	Charcoal	8290 ± 140	7600–6850	9550–8800
UGAMS#10147	Charcoal	8410 ± 30	7550–7450	9520–9400
UGAMS#10150	Charcoal	8410 ± 30	7550–7450	9520–9400
UGAMS#01844	Charcoal	8820 ± 60	8220–7720	10,170–9670

[a]Extended counting.

The site of Takarkori is located along the Takarkori wadi in the Tadrart Acacus Mountains in southwest Libya, central Sahara (Figure 1). This sandstone massif is famous for its majestic rock art (Mori 1965; di Lernia and Zampetti 2008) and rich associated archaeology (Mori 1965; Cremaschi and di Lernia 1998). Takarkori is a large rockshelter open toward the west, and located ~100 m above the wadi bottom. The Algerian-Libyan border passes through the area. The site was in a strategic position even in the past, dominating the wadi that connects the Tadrart Acacus Mountains to the western lowlands leading to the Tassili Plateau, itself an area characterized by a mosaic of different micro-environments.

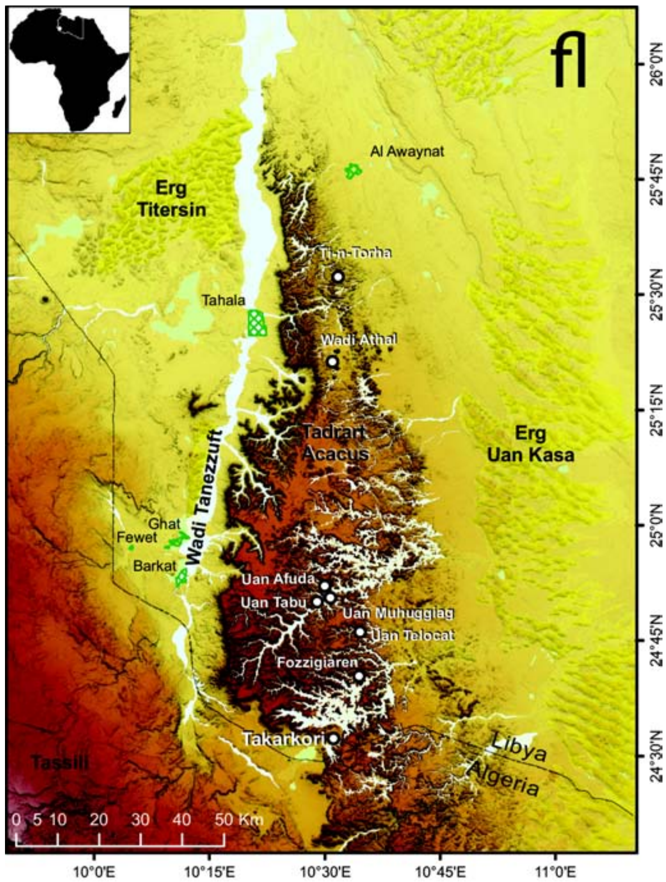


Figure 1 The Tadrart Acacus Mountains (SW Libya) with the main archaeological sites shown.

Most of the Holocene human occupation is presented at Takarkori (Biagetti et al. 2004; Biagetti and di Lernia 2007; di Lernia et al. 2012; Dunne et al. 2012). The first occupation dates from the early Holocene, featuring the semi-residential dwellings of Late Acacus foragers. This long-term and diversified occupation is characterized by the remains of stone structures, large fireplaces, and other features. All of these artifacts support the idea of a semi-residential occupation, based on the exploitation of locally available food resources such as wild cereals, fish, and small- to medium-sized animals (Olmi et al. 2011). ^{14}C dates bracket the chronology of the Late Acacus occupation at Takarkori between ~8300 and 6100 BC. The Pastoral Neolithic, or Early Pastoral, is also well attested there:

the oldest phase at ~6400–5300 BC has been severely affected by erosive phenomena, but several fireplaces and human burials located in a limited area of the rockshelter give insights into the lives of the earliest Saharan cattle herders (di Lernia and Tafuri 2013).

The Middle Pastoral occupation consists of a series of organic sandy soils alternating with several fireplaces. These features indicate a shorter and/or seasonal occupation compared to the previous phases. The large quantity of potsherds are the most significant artifacts. The ^{14}C dates for the Middle Pastoral period are in the range ~5200–3700 BC. The last presence refers to the Late Pastoral (~3700–2700 BC), a phase characterized by seasonal visits from groups of specialized herders. The sequence is closed by a thick layer of dung, a common feature in the area (Cremaschi and di Lernia 1998; Mercuri 2008).

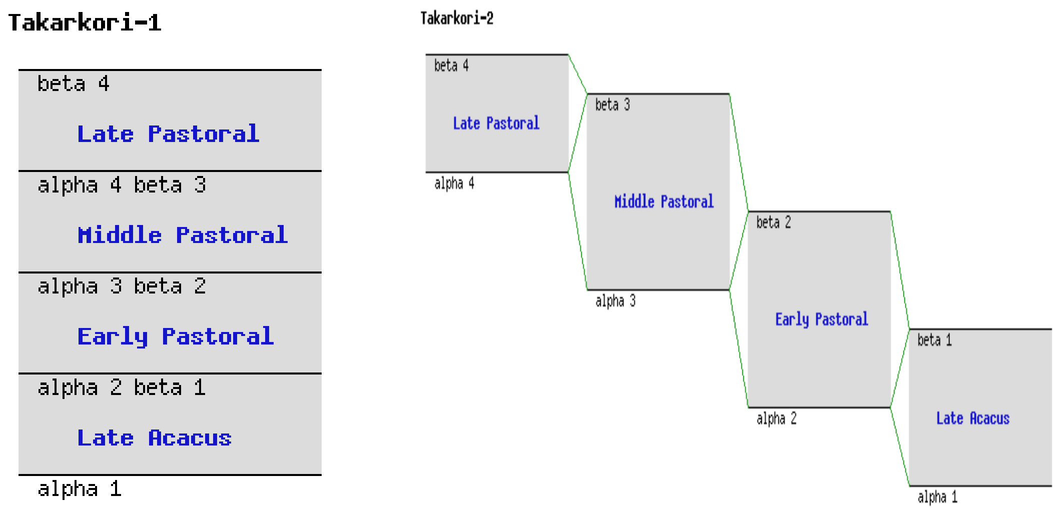
Material culture and main archaeological features of human frequentation at Takarkori finely match the general Holocene sequence we have for SW Libya (e.g. Cremaschi and di Lernia 1998, 1999; di Lernia 2002). The transitions in the area are generally related to or even triggered by major climatic discontinuity (Cremaschi and di Lernia 1999). Therefore, the beginning and end of each cultural phase should be considered theoretically clear-cut. This was never true, of course. Seen in a larger scenario, when the first early Holocene colonizers arrived, around 10,000 BC, they had to familiarize themselves with unknown environments. The waves were multiple and probably from different areas: the archaeological record is still too poor to allow a finer definition. The introduction of domesticates—roughly dated between 6400 and 6000 BC—did not produce a population replacement: yet, hunter-gatherers and pastoralists likely cohabited for generations and encapsulated groups might have survived in specific locations for centuries (di Lernia, in press).

In this direction, also considering the erosional phenomena that heavily affected the depositional history, the most parsimonious hypothesis to be tested—thanks to a large number of dates coming from a single context—is the existence of clear boundaries between cultural phases or overlaps. On the basis of the available literature as well as a large number of ^{14}C dates coming from the region (e.g. Cremaschi and di Lernia 1999; di Lernia 2002; di Lernia and Tafuri 2013), the most valid model (so far) is made of a cultural phase with clear start/end limits. We are testing here the validity of these limits in a single context and a rather complete—even if eroded—stratigraphic sequence from Takarkori rockshelter.

RESULTS

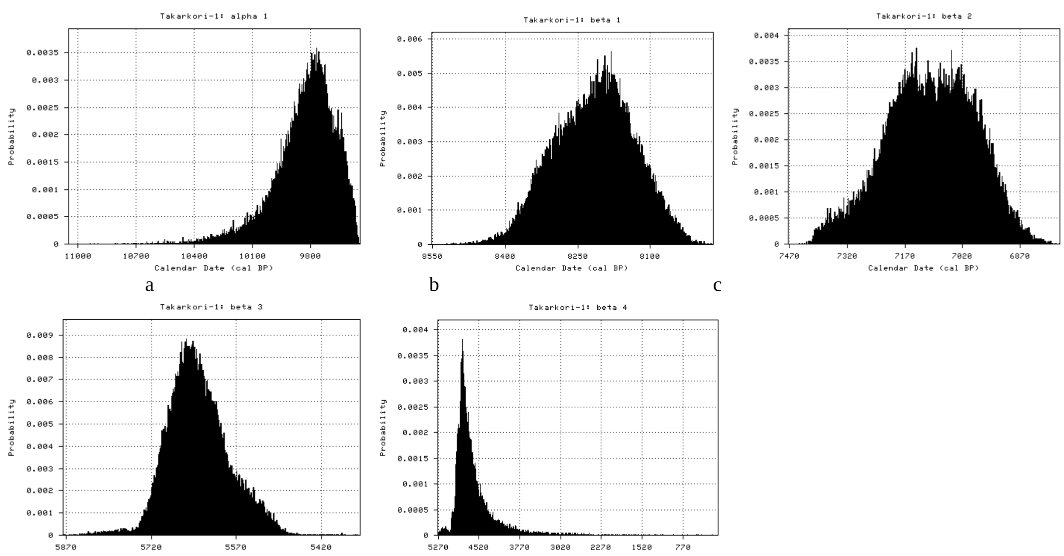
We do not have absolute *a priori* data for any phase of this site, however, we do understand their stratigraphic relationships. We have tested 2 models of the relationships of these phases. The first model suggests that the phases abut each other in time (Figure 2a) and the second model suggests that they overlap each other (Figure 2b). The posterior probability density plots for each boundary are shown on Figures 3a–e for Model 1 and Figures 4a–h for Model 2, respectively.

For Model 1, the highest posterior density (HPD) region for alpha 1, at the beginning of the Late Acacus (LA) phase, is the interval 10,080–9570 yr cal BP. The result is almost the same for Model 2. The HPD region for the oldest calibrated date is 10,170–9670 yr BP. These intervals are the shortest ones that could be constructed to include 95% posterior density (Table 2). The same analysis for the youngest boundary of the LA phase (also the oldest boundary for the Early Pastoral [EP] phase) has an interval of 8370–8070 cal BP for Model 1, and 8390–7910 cal BP for Model 2, at 95% posterior density. Then, the HPD region for the oldest calibrated date of the end of the EP phase is 7420–6890 cal BP and for the beginning of the MP phase is 7160–6790 cal BP. These intervals are the shortest ones that could be constructed to contain 95% posterior density.



a b

Figure 2 Relative chronological information (a) for the abutted Model 1 and (b) for the overlapped Model 2



a b c d e

Figure 3 The boundaries for the different phases according to the abutted Model 1: a – earliest boundary for Late Acacus; b – latest boundary for Late Acacus and earliest for the Early Pastoral; c – latest boundary for Early Pastoral and earliest boundary for the Middle Pastoral phase; d – latest boundary for the Middle Pastoral and earliest boundary for the Late Pastoral; e – latest boundary for the Late Pastoral.

The HPD region for alpha 3 of the Middle Pastoral (MP) phase and for beta 2, the youngest boundary for the EP phase, has an interval from 7300 to 6900 cal BP in Model 1. Model 2 has even wider boundaries, calculated as a result of the overlap between alpha 3 and beta 2: 7370–6690 and 7650–6900 cal BP, respectively. Then, the HPD region for the oldest calibrated date of the end of the EP phase is 7420–6890 cal BP and for the beginning of the MP phase is 7160–6790 cal BP. These intervals are the shortest ones that could be constructed to contain 95% posterior density.

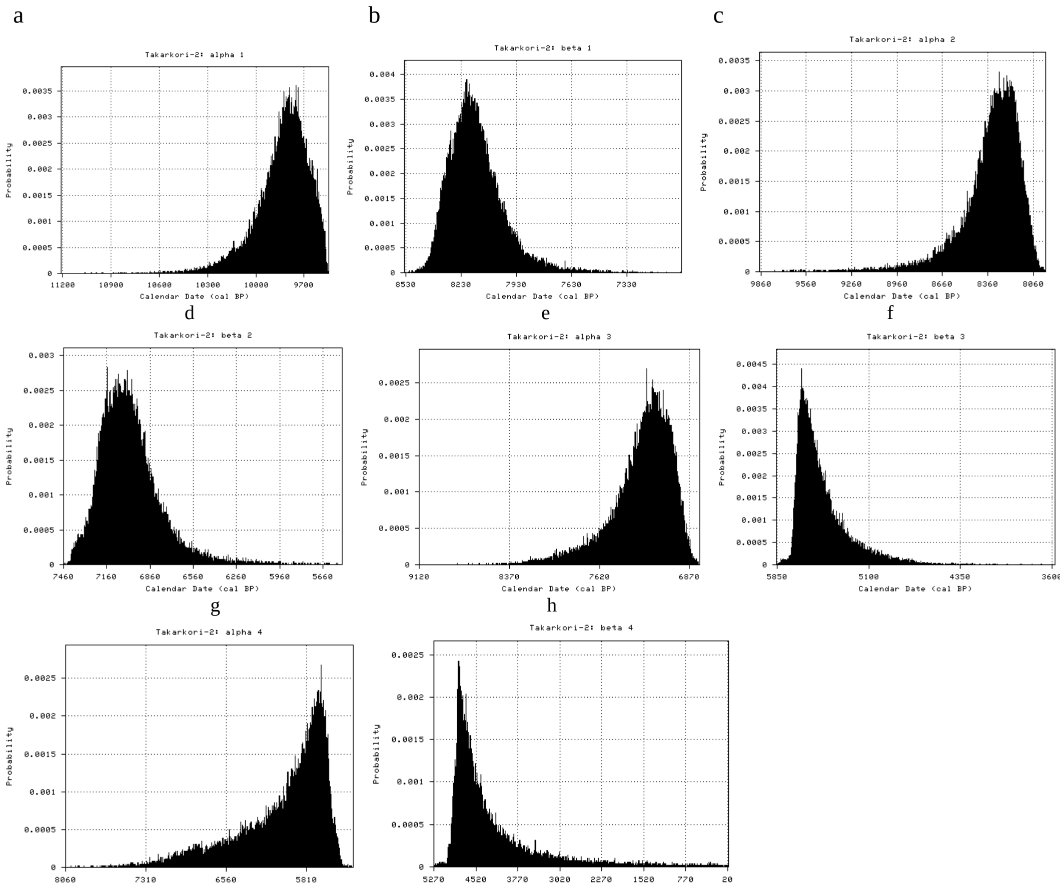


Figure 4 Earliest and latest boundaries for the different phases according to overlapped Model 2: a and b – for Late Acacus phase; c and d – for Early Pastoral phase; e and f – for Middle Pastoral phase; g and h – for Late Pastoral phase.

Table 2 The boundary of the beginning (alpha) and the end (beta) of each phase of Takarkori rockshelter at 95% HPD (highest posterior density) regions.

Phase		Elapsed time between HPD intervals, cal BP at 95% HPD regions	
		Model 1, abutted	Model 2, overlapped
LA	Alpha 1	10,080–9570	10,090–9570
	Beta 1	8370–8070	8390–7910
EP	Alpha 2	8370–8070	8620–8060
	Beta 2	7300–6900	7370–7350, 7340–6690
MP	Alpha 3	7300–6900	7650–6900
	Beta 3	5730–5530	5740–5150, 5130–5120
LP	Alpha 4	5730–5530	6620–6610, 6550–6520, 6510–5510
	Beta 4	5020–3960, 3940–3890	5020–3660, 3640–3580, 3550–3530, 3480–3460, 3290–3280

The same analysis for the youngest boundary of the MP phase (also the oldest boundary for the Late Pastoral [LP] phase) results in the interval 5730–5530 cal BP for the abutted model; in the case of the overlapping model, the beta 3 boundary is extended to the range 5740–5120 cal BP and for alpha 4 to 6620–5510 cal BP at 95% posterior density. However, in the overlapping model these boundaries are even wider: 5710–5480 cal BP and 6070–5590 cal BP for beta 3 and alpha 4, respectively. Such wide boundaries appear contradict the paleoclimatic and archaeological data, which both favor a very abrupt change at around 5200–5000 ^{14}C BP (5900–5760 cal BP: Cremaschi and di Lernia 1999; di Lernia 2002; Cremaschi et al. 2006).

The HPD region for beta 4, the youngest boundary for the LP phase, is the interval 5020–3890 cal BP and 5020–3280 cal BP for both Model 1 and Model 2. The HPD region for the youngest calibrated date of the end of the LP phase is 5040–4650 cal BP. These intervals are the shortest ones that could be constructed to contain 95% posterior density.

The estimation of the time elapsed for the LA period is shown in Figures 5a and 6a. The 95% posterior density HPD region for this period is 1300–1710 yr in Model 1 and 1300–2060 yr in Model 2. Thus, the overlap between the LA and EP periods for this model is about 460 yr. If we compare these values with the time elapsed, calculated directly from calibrated dates, this interval would be 1230–2140 yr, which is even longer than the interval for the overlapped model. The time elapsed for the EP period is shown in Figures 5b and 6c. The 95% posterior density HPD region for this period is 860–1380 yr and 850–1810 yr for Models 1 and 2, respectively.

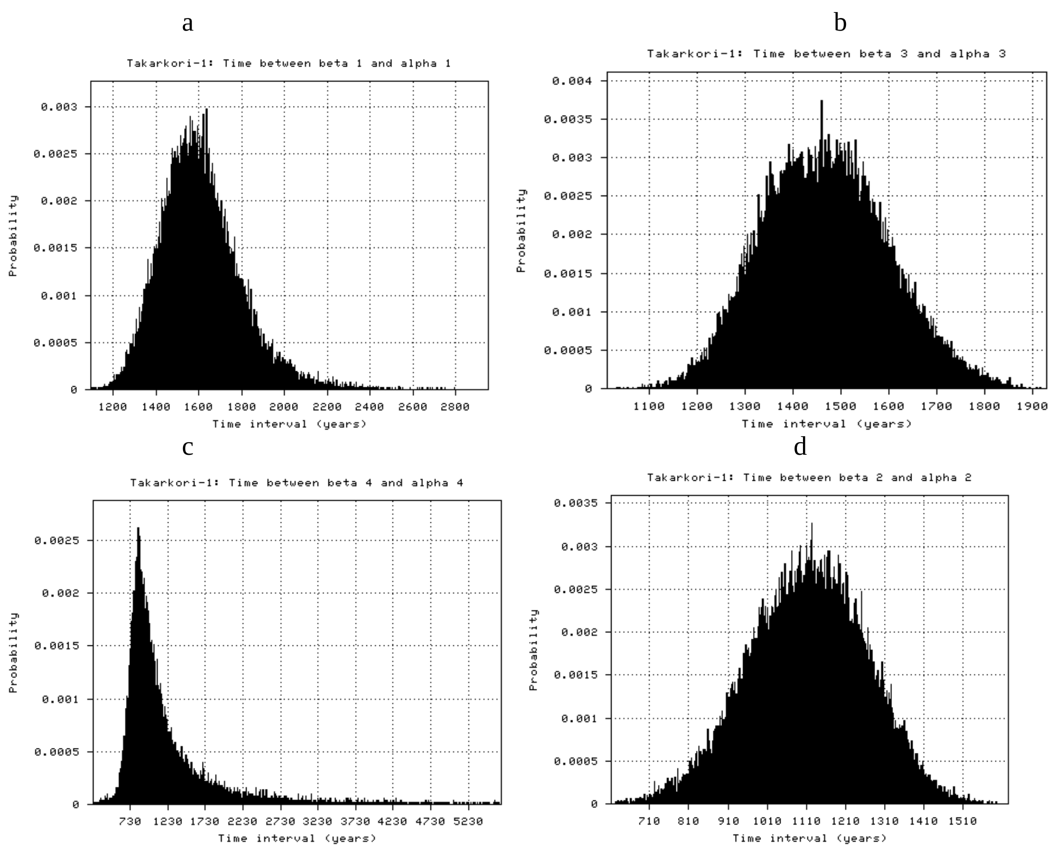


Figure 5 The elapsed time for the different phases according to the abutted Model 1: a – Late Acacus phase; b – Early Pastoral phase; c – Middle Pastoral phase; d – Late Pastoral phase.

The estimation of the time elapsed for the MP period is shown in Figures 5c and 6e. The 95% posterior confidence region for this period is 1240–1690 yr and 1250–2270 yr for Models 1 and 2, respectively. These intervals are narrower than the interval that could be calculated directly from the calibrated ^{14}C dates at 95% posterior confidence regions.

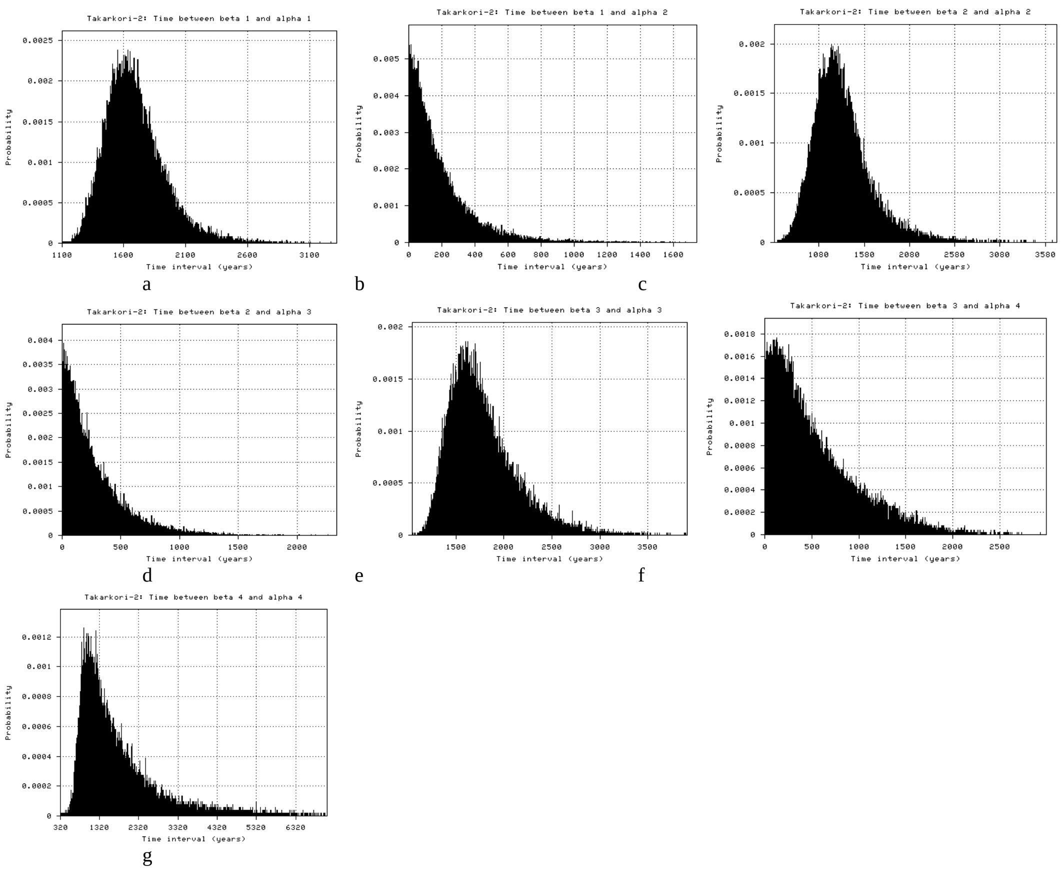


Figure 6 The elapsed time for the different phases and the overlapped boundaries between them: a – Late Acacus; b – between the upper boundary for Late Acacus and the lower boundary for Early Pastoral; c – Early Pastoral; d – between the upper boundary for Early Pastoral and the lower boundary for Middle Pastoral; e – Middle Pastoral; f – between the upper boundary for Middle Pastoral and the lower boundary for Late Pastoral; g – Late Pastoral.

Finally, the estimation of the time elapsed for the LP period is shown in Figures 4d and 5g. The 95% posterior confidence region for this period has 4 separate intervals between 650 and 2690 yr for both models, so we did not limit this phase with any *a priori* value.

If we change the model of interaction between these phases to the overlapped construction shown in Figure 5, the boundary HPD regions would also be changed. Alpha 2 (at the beginning of the EP phase) and beta 1 (at the end of the LA phase) would also be slightly changed (see Figures 5b and c and Table 2, 95% posterior confidence regions). However, for the phase boundaries beta 2 and alpha 3 (Figure 6d and e), these changes are already quite significant and expanded for more than 300 yr at the 95% posterior confidence regions. The most significant expansion of the boundary was noted for the alpha 4 boundary (Figure 6g), about 900 yr in the case of the overlapped Model 2 compared to the abutted Model 1.

The elapsed time period for each phase is also expanded (Figure 6a–g) for about 300–400 yr, although only for the LP phase, which is the same in both models. The time intervals between the phases for overlapped Model 2 were estimated as follows: 0–460 yr between LA and EP phases; 0–590 and 630–640 yr between EP and MP phases; and 0–1050, 1080–1100, 1110–1120 yr between MP and LP phases (Table 3). The abutted Model 1 is preferable from an archaeological point of view. However, the overlapped Model 2 can also be justified.

Table 3 The duration of each phase and their interactions for abutted Model 1 and overlapped Model 2 at 95% HPD regions.

	Elapsed time between HPD intervals, years at 95% HPD regions	
Phase	Model 1, abutted	Model 2, overlapped
LA	1300–1710	1300–2060
LA–EP	0	0–460
EP	860–1380	850–1740, 1760–1810
EP–MP	0	0–590, 630–640
MP	1240–1690	1250–2270
MP–LP	0	0–1050, 1080–1100, 1110–1120
LP	650–660, 670–2370, 2390–2610, 2680–2690	650–660, 670–2370, 2390–2610, 2630–2690

CONCLUSIONS

Stratigraphic sequences in desert environments, even when sheltered or otherwise protected, represent a serious challenge for archaeologists and other scientists. The superimpositions of sandy sediments, intermixed with fireplaces, stone structures, and other features, often create authentic palimpsests, severely exposed to sin- and post-depositional disturbances.

So far, the chronological reconstruction of Holocene human occupation in the Acacus and surroundings (SW Libya) has based on the combination of environmental data, material culture, and, where available, stratigraphic relations. Yet, rarely have we had significant numbers or ^{14}C measurements from the very same site, hampering the possibility to statistically assess the chronological boundaries and duration of each cultural phase. Takarkori rockshelter represents an outstanding exception, with around 50 measurements, the largest sample from the whole central Sahara from a single site. Here, we have compared 2 model interactions (abutting vs. overlap) between the 4 phases of human occupation: analysis of the models using a Bayesian approach shows that Model 1 is more likely. According to the *a priori* assumption, the maximal duration of the Late Acacus phase was 1710 yr at 95% posterior confidence regions. This duration is more accurate and seems to correspond to archaeological and climatic data better than the maximum duration 2140 yr, which is calculated from the calibrated ^{14}C date without Bayesian modeling.

The duration of the Early Pastoral phase was between 850 and 1380 yr at 95% posterior confidence and 990–1440 yr at 68% posterior confidence, with a direct calculation from the calibrated date of 580–1430 yr. In the same way, Model 1 has allowed us to define the duration for both Middle and Late Pastoral phases.

From an archaeological point of view, the abutted model fits better with the available information from the study area—especially the main climatic events—even if the transition between Late Acacus and Early Pastoral phases still remains to be fully defined. For this crucial cultural change, both abutted and overlap models could be valid and only additional Early Pastoral measurements from other sites can help to better define the nature and meaning of chrono-cultural relationships: the local assessment of the impact of the so-called 8.2k event could be particularly useful. It is true that the boundaries of the other main cultural phases are built upon a large set of ^{14}C measurements from quite a large region (Cremaschi and di Lernia 1998, 1999; di Lernia et al. 2013), and the Takarkori series fits well. In particular, the Bayesian analysis of the transition between Early to the Middle Pastoral phases seems to be consistent and confirms the existence of a chronological gap, whose significance has been largely discussed elsewhere (di Lernia 2002). Thus, using the Bayesian approach, we can improve not only the calibrated ^{14}C dates but we can also more precisely define the boundary for each phase and its duration, to be then matched against a larger regional analysis.

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