Inside the “African Cattle Complex”: Animal Burials in the Holocene Central Sahara

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Abstract
Cattle pastoralism is an important trait of African cultures. Ethnographic studies describe the central role played by domestic cattle within many societies, highlighting its social and ideological value well beyond its mere function as ‘walking larder’. Historical depth of this African legacy has been repeatedly assessed in an archaeological perspective, mostly emphasizing a continental vision. Nevertheless, in-depth site-specific studies, with a few exceptions, are lacking. Despite the long tradition of a multi-disciplinary approach to the analysis of pastoral systems in Africa, rarely do early and middle Holocene archaeological contexts feature in the same area the combination of settlement, ceremonial and rock art features so as to be multi-dimensionally explored: the Messak plateau in the Libyan central Sahara represents an outstanding exception. Known for its rich Pleistocene occupation and abundant Holocene rock art, the region, through our research, has also shown to preserve the material evidence of a complex ritual dated to the Middle Pastoral (6080–5120 BP or 5200–3800 BC). This was centred on the frequent deposition in stone monuments of disarticulated animal remains, mostly cattle. Animal burials are known also from other African contexts, but regional extent of the phenomenon, state of preservation of monuments, and associated rock art make the Messak case unique. GIS analysis, excavation data, radiocarbon dating, zooarchaeological and isotopic (Sr, C, O) analyses of animal remains, and botanical information are used to explore this highly formalized ritual and the lifeways of a pastoral community in the Holocene Sahara.

Introduction
Stone monuments, rock art and cattle: an African legacy
Early Holocene cattle-based pastoralism is the oldest form of productive economy in Africa, which precedes agriculture [1,2]. Despite the idea of an independent African domestication of Bos primigenius remains still controversial [3,4], a genetic input of African aurochs during the long and discontinuous domestication process is possible [5]. Timing and mechanisms of livestock spread in Africa have been studied primarily combining radiocarbon dates of morphologically domestic remains with specific regional trajectories [6]. Secondary exploitation of cattle appears much later, with the earliest evidence of dairying from the central Sahara around 6100 BP [7].

Notwithstanding ecological barriers and diseases such as trypanosomes [8], cattle pastoralism spread all over the continent, becoming a momentous segment of African economy and society. Even today, relations between herdsmen and their animals, especially in Eastern Africa, are particularly strong and well beyond the mere use of cattle as ‘walking larder’ [9]. Travellers, explorers and ethnographers of the 19th and early 20th century gave vivid narratives about the crucial importance of cows and bulls: Herskovits [10] coined the concept of “African Cattle Complex”, underlining the role of these animals within many African populations.

Bovines represent the primary wealth and are often used to pay bride and blood fines, being the basis for social prestige. Only rarely eaten, their slaughtering is often strongly socialized and special places are required for this purpose e.g., [11–13]. There is therefore scarce doubt that cattle exploitation and pastoral identity in Africa largely overlap e.g., [4,11–16] and roots of this African legacy must be found in its remote past.

Given the extraordinary historical depth of cattle management in Africa, it is not a surprise that most archaeological investigations focused on defining nature and organization of African pastoralists [6,17]. However, the exploration of ideological and ritual
aspects was mostly directed towards the study of human mortuary practices [18,19], monumental architecture [20,21] and rock art [22,23]. Yet, cattle and pastoral activity are obsessively present in African iconography: in the Sahara, more than 60% of art panels portrait cattle or cattle-related scenes [24].

Artworks of bovidian/pastoral style are thus the tangible evidence of a shared heritage ideologically focussed on cattle. However, problems in its dating [25] make it difficult to relate settlement and subsistence data with the Saharan pastoral ideological world.

Another important archaeological evidence of cattle centrality in the African prehistoric pastoral world is represented by stone monuments with articulated or disarticulated remains of bovines, repeatedly interpreted as the expression of the “African Cattle Complex”, such as those of Nabta Playa in Egypt [26] or Adrar Bous in Niger [27–29]. More recent research relates the presence of accumulations of cattle bones, defined by the authors “Tenerian meals”, to feasting activities [30]. Further contexts with possible ritual depositions of cattle are reported from Talak–Timenrsoi in western Air, Niger, and dated between 5400 and 4800 BP [28]. The site of Mankhor, in the Algerian Tadrart, dated between 5525 and 4865 BP, shows evidence of ritual deposition [31]. The ritual interment of cattle remains appears however to be a long standing habitus, as testified by other Niger sites dated as late as 3500 BP [28], plus for example the evidence from the Nile valley e.g., [32].

Cattle, stone monuments and rock art appear to be important elements of African prehistoric pastoral societies, but they rarely occur together so as to be multi-dimensionally explored: the Messak plateau (SW Libya) in the central Sahara represents an outstanding exception (Fig. 1). Here, engravings portraying pastoral activities—which include the vivid representation of cattle sacrifices (Fig. 2)—are common and often in spatial relations with stone monuments. Some of these structures were already excavated in the 1990s [33]: they revealed the existence of deliberate depositions, mainly of cattle, with engravings of bovines strictly associated. A specific project was later launched (Messak Ceremonial Monuments Project, MCMP, 2007–2010) with the aim to explore the complexity of this cultural phenomenon, either in time or space.

This has been achieved through a campaign of surveys and excavations of stone monuments and associated rock art, combining environmental information, GIS spatial analysis, archaeological data, radiocarbon chronology, zooarchaeology, archaeobotany and isotopic investigation.

Figure 1. The Messak plateau and surroundings. The white insert shows the area of fieldwork (2000; 2007–2010).

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Middle Pastoral herders of the central Sahara

Cattle and small livestock were introduced in the Central Sahara at the end of the 8th millennium BP, and slowly adopted by local groups of hunter-gatherers [2]. In the Acacus and Messak mountains (SW Libya) a full exploitation of domesticates, which included dairying [7], is dated to the Middle Pastoral (6100–5000 BP), a cultural phase generally characterized by wet and warm environmental conditions [34–36].

Past geoarchaeological surveys and excavations helped to define settlement system, food security, mortuary and social practices of Middle Pastoral groups [37–39]. This was mainly achieved in the Acacus massif and neighbouring dune fields (Erg Uan Kasa), thanks to the good state of preservation of stratigraphic contexts in the mountain range, which yielded a rich archaeological record [37]. The territorial scale of analysis also allowed for the understanding of mobility patterns between different ecological niches of these cattle herders [38–40], which were regulated by the high seasonality of monsoonal precipitation recorded for the middle Holocene [34]. Large and semi-residential sites are abundant along the former shores of lakes in the dune fields; they were likely occupied during the rainy season (summer), while during the drier season (winter) herders concentrated in the mountain range, as also indicated by pollen data [35].

The Acacus-Uan Kasa model might also apply to the Messak plateau and the vast Edeyer of Murzuq, where solid locational relations might have linked the two areas. In the latter, several rich Middle Pastoral sites were mapped and some were excavated [37,41]. They can be reasonably interpreted as summer semi-residential sites, exploiting the water-rich areas surrounding the lakes [34]. Unlike for the Acacus-Uan Kasa system, we found poor evidence of Holocene settlement in the Messak, with a dozen of Middle Pastoral contexts, generally showing ephemeral and light occupation [42,43]. Along with dated sites, a large number of contexts lack chronologically diagnostic features: some or many of them could be of Middle Pastoral age. As a general tendency, however, no Holocene settlement site, regardless of its chronological attribution, shows complex and articulated features. In this sense, the paucity of settlements (be it numerical or in terms of complexity) contrasts with the richness of stone ceremonial monuments [33,44–49], rock art [47–49] and quartzarenite quarrying [50]. Many of these archaeological contexts might belong to the Middle Pastoral, as recently proposed for the “Messak school” engravings [25].

The Messak. Environmental and archaeological background

Our study area is a large plateau which extends over more than 15,000 km² between 24° and 26° 30’ latitude N, and 11° and 13° longitude E [51]. It can be divided into two adjoining regions separated by the Tilemsin corridor: Settafet (“black”, in local language) and Mellet (“white”). The Messak is a cuesta type massif cut into the Jurassic to Cretaceous Messak Sandstone, gently tilted eastward and delimited by an abrupt scarp. The maximum altitude is 1200 m asl. A dense network of fossil wadis with a dendritic pattern dissects the plateau, originated in the Tertiary under a pluvial climate. The present climate of the region is hyperarid: mean annual temperature is 22–25 °C; mean annual rainfall is 0–10 mm. Both climate and palaeoclimate depend on low altitude pressure and winds over the continent and the seasonal migration of the Intertropical Convergence Zone, resulting in belts of monsoonal climate with summer rains and dry winters [52].

The flora is still not fully known, but most of the species described for the central Sahara [53] were observed in the field. Acacias include Faidherbia albida, Acacia tortilis and Amídotoca. Shrubs of Corisulea monacantha, Pulicaria crispa, Punicum turgidum and Spigiosista pungens are common. Desert savannah and Saharo-montane vegetation, typical of the Saharan Transitional zone [54], is prevalent in the wadis.

The main physiographic units of the massif correspond to residual surfaces (hamada and serir), solutinal depressions, slope deposits, and a composite escarpment [51]. The typical landscape of the Messak plateau is the black hamada surface, whose clasts are coated by a dark Mn-rich varnish [55], interrupted by wide serir spots. The desert pavement overlies relict and complex rubified paleosols, which are discontinuously present on the plateau. These formed under pluvial phases since the early Pleistocene. The most recent pedogenesis is dated to the middle Holocene [56].

The hamada is now a palimpsest of lithic scatters dating from Early Stone Age to historical times [43,57]. Holocene occupation features hundreds of funerary and ritual structures [33,43,44], whereas, as already emphasized, only light and ephemeral dwellings were recorded [37,42,43,58,59]. Rare deposits are preserved in rock shelters [60]. The most impressive Messak feature is rock art: the wadi areas are dotted by thousands of engraved panels of Holocene age [25,47–49,61,62].

The Messak Ceremonial Monuments Project (MCMP)

The first monuments with animal remains were found during a rescue operation to assess damages caused during oil prospecting [33,42]. These added to the results of the excavation of a standing stone located at In Habeter, also containing cattle remains [63]. Such features suggested the existence of ceremonies clearly connected to pastoral rituals focused on cattle ideology [33].

To assess the extent of the phenomenon, and to define its nature and meaning, we launched the “Messak Ceremonial Monuments Project” (MCMP 2007–2010).

The research has been carried out within the activities of The Archaeological Mission in the Sahara, Sapienza University of Rome and the Department of Archaeology (DoA), Trippoli, directed by SDL. All necessary permits were obtained for the field studies and laboratory analyses (including destructive ones) presented here.

Results and Discussion

Our data convey to suggest that during the middle Holocene (6080–5120 BP or 5200–3800 BC) the Messak plateau homed the
Corbeilles and rock art: a GIS approach

The sources for our GIS platform are published and unpublished information, together with our fieldwork data, for a total of 197 structures (Text S1; Table S1). Depending on the different sources, quantity and quality of data for each structure can vary from a simple positioning to a full excavation record. To overcome this heterogeneity, the analyses were first performed on the spatial location of the structures, also using satellite imagery; for each structure we have analysed topographical and geomorphological setting, together with the hierarchy, geography and morphology of the related wadi (Table S1).

The distribution map proves the widespread presence of corbeilles all over the region, but for the north-eastern Settafet (Fig. 3). The structures are mainly located in specific and recurrent locales: they are placed on the hamada (79%), along the middle courses of the principal wadis (79%), in correspondence with their widest meanders (86%) and close to the wadi bank (<75 m, 83%).

The geomorphology of these locales corresponds to valleys with flat floors and steep sides [51]. Wadi cuts are mostly attributed to groundwater seepage erosion; it is likely that these parts of the wadis experienced high water availability thanks to groundwater coming to light a few hundreds of meters ahead. These places thus represented favourable areas for grazing and water supply in an otherwise harsh landscape.

The minimum reciprocal distance between monuments, the distance of the structure(s) from the wadi banks and the accessibility to the ancient river are important elements to define the micro-topographic features of these contexts. Corbeilles are commonly very close to one another (ca. 41% under 30 m), creating ‘aggregate’ contexts. Interestingly, very remote and isolated structures are not rare (> 15%).

The striking proximity between monuments is mirrored by the analysis of the Average Nearest Neighbour, which shows a high index of clustering (Observed Mean Distance 1546.52 m; Expected Mean Distance 4125.53 m; NN ratio 0.37; z Score −16.79; p-value 0.0000), highlighting the non-random distribution of the structures all over the region and validating the regional organization of the cultural phenomenon. Analysis of density of corbeilles’ location, based on the kernel method [64], identifies the existence of four areas with very high clustering, located respectively at Wadi Bedis and Wadi Tilizaghien (Northern Settafet); Wadi Taleschout -possibly being part of a wider cluster together with Tin Sharuma- (Southern Settafet); and Wadi Ankhbrit (Mellet). Although the chronological relationships between the monuments cannot be ascertained on the basis of survey information alone, the presence of many and very similar structures in specific locales should be in any case interpreted as evidence of important places in the pastoral landscape.

Most interestingly, none of the architectural features of the corbeilles (size, elevation, building elements, presence and type of standing stone) show significant distribution in the landscape: this reinforces the value of the corbeille itself (and not of its building elements) as a codified landmark in the Messak Middle Pastoral world.

The distribution of the corbeilles and particularly that of the main concentrations of monuments largely matches that of rock art. Combining different sources on rock art contexts, we identified 102 scenes (Table S3) clearly referable to a Middle Pastoral phase (following [25]), whose spatial distribution and density are extremely similar to those of the corbeilles (Fig. 3). In these rock art scenes, cattle is obsessively present as an isolated subject or as part of complex scenes referring both to everyday life duties and more symbolic settings. Interestingly, the only three artworks depicting the slaughtering of cattle are all located in the northern area, where one of the most significant concentrations of corbeilles occurs (at least in one case, 07/110 C1, the structure with cattle remains is located immediately above the engraving).

Survey in the Northern Messak Settafet

The rationale of the MCMP fieldwork was to assess the distribution of stone monuments and to investigate their correlations with the landscape. A series of sampling areas were set along an ideal N-S transect intercepting the main geographic and physiographic units, following the course of one of the main fossil hydrographical arteries of the Messak (In Tullult, In Erahar, Wadi Bedis; Fig. 4; Text S2). This fieldwork adds to research undertaken in the 1990s in the areas of Tin Eimesnis (1 and 2) and In Habeter III (see [33]).

A total surface of approximately 75 km² was investigated, with 219 Holocene archaeological contexts identified (Text S2; Table S2). Most of them are conical tumuli, followed by stone structures and other stone features: the corbeilles are 34. The chronological or cultural attribution is difficult: most of the contexts are generically referred to Pastoral age; many structures are of recent, historical occupation. The contexts attributed to the Middle Pastoral are a few dozens.

However, it is clear that some locations, i.e. the most (and probably the few) geomorphologically favourable places for grazing and water supply, assumed a key role for the cultural and ritual activities of the Middle Pastoral herders, and were reoccupied and reused by later pastoralists. This evidence is also supported by the high concentration in a few areas of trapping/tethering stones (TS): these stones, generally represented in rock engravings as hunting devices e.g., [48], are made of slabs or boulders of different size (up to 1 m) with notches or grooves to block a rope. Even if reused over time (Fig. 5), the very large quantity of these stones in places clearly unsuitable for hunting activity -such as the area of Tin Eimesnis I (256 TS) and the Bedis meander (around 07/39 and 07/40: 187 TS; around 07/68: 126 TS)-, suggests a functional interpretation of these stones as tethering elements for domestic animals. Should they either represent the archaeological evidence of the gathering of several people (as potentially suggested by the presence of ceremonial monuments) or the reuse over time of the same place, the outcome is the same: these concentrations of tethering stones mark, together with the densest clusters of ceremonial monuments, locales of social importance and enduring value for Messak pastoral groups.

The excavations of stone monuments

As a whole we excavated 42 stone monuments, mostly in Wadi Bedis meander. Most of the monuments were corbeilles (26), together with stone structures (7), tumuli (4), stone platforms (2) and other elements (Table 1; Fig. 5): when monuments were very close to each other, extended excavations or test pits were carried
Figure 3. Desktop and GIS analysis. Distribution maps of corbeilles (A) and Middle Pastoral engravings (C–red triangle indicates the artworks depicting the slaughtering of cattle) and their density analysis (B, D). The four densest clusters are indicated (I–IV). doi:10.1371/journal.pone.0056879.g003

Figure 4. Detail of the area of intensive survey. General area (A); detail of Transect 5 (B); magnified view of red square in Transect 4 (C). The excavated monuments are indicated by full dots (black for the corbeilles, white for the other monuments) and their Id number (see Table 1 for details). doi:10.1371/journal.pone.0056879.g004
out to assess their function and possibly verify the chronological correlation.

In sum, 22 between structures and associated features yielded faunal remains; stone tools or potsherds are present in 15 contexts; and 9 monuments shown slabs/boulders with rock art engravings.

Twenty-two structures were radiocarbon dated (on charcoal, charred animal bones), indicating a time span for the animal burial phenomenon in the region between 6080 and 5120 BP (approximately 5200–3800 BC: Table 2). The most ancient date refers to structure 00/301, a small deflated tumulus with animal remains coming from distinct fire points, very close to an empty, but not datable, corbeille (00/301a). The earliest date for a corbeille itself comes from structure 07/39 C6, dated to 5660 ± 30 BP. The dates cluster between approximately 5400 and 5200 BP. Two dates on small features, both from Wadi Bedis meander, are much later and point to Final Pastoral and Garamantian visits, reinforcing once more the key role of these specific places over the centuries.

The corbeilles differ in their architectural settings, varying from a simple type characterized by a circular perimeter made of slabs vertically set in the ground and often a central standing stone, to more complex structures with external annexes and standing stones. Fillings and stratigraphic settings vary according to the location and the substratum. One or two series of superimposed stones alternating with sand sediments can be set directly over the bedrock or cover a pit dug in the bedrock. The accumulation of faunal remains, including the skull, is usually located at the bottom of the structures.

Stone monuments are not static entities. They were part of a living landscape—sometimes reopened or revitalised. This is evident in some ab antiquo ‘plundered’ monuments, such as structures 00/300 and 07/39 C2, and is evident in the rock markings within the monuments and on top of them [25]. Corbeilles are not isolated features: stratigraphic relations, analysis of faunal remains and radiocarbon measures helped to better articulate the rituality involved in the use of these monuments. Larger excavations allowed us to reconstruct some of the relations between structures (such as 07/39 C2 and C3; 00/556 and its external stele), where the remains of the slaughtered animals were disposed inside and outside the different monuments.

Archaeological materials

Although the filling of the structures can occasionally include archaeological finds, firmly associated materials fall in two main categories: stone artefacts (especially maces) and pottery.

As a whole (Table S4), we found 16 maces from 11 different structures, mostly corbeilles. Maces show similar morphology and opportunistic features (Fig. 6): made on quartzarenite, they are heavy tools (ca. 2.8 kg on average) exclusively produced by means of façonnage technique. They can feature a very worn handle, whereas the active protruding part was most likely re-sharpened just before its last use (C. Lemorini unpublished data). They were
Table 1. Main features of excavated contexts with evidence of rituals related to animals, sorted by geographic position.

| Id     | Structure Type | Annex | Standing stone | Age C14 BP | Fauna               | Archaeological Materials | Rock art associated with the structure* |
|--------|----------------|-------|----------------|------------|---------------------|--------------------------|----------------------------------------|
|        |                |       |                |            |                     |                          |                                        |
| 1      | simple corbeille | —     | 1 central      | —          | —                   | —                        | —                                      |
| 2      | deflated tumulus | 2     | —              | 6080±80    | Bos taurus, Ovis vel Capra | 3 maces, 1 gouge          | 1 potsherd, rockers, plain edge (Middle Pastoral) |
| 3      | simple corbeille | —     | —              | 5610±40    | Large ungulate      | 1 bifacial tool           | —                                      |
| 4      | complex corbeille | —     | 1 central      | 5400±30    | Bos taurus          | 2 bifacial tools          | —                                      |
| 5      | simple corbeille | —     | —              | 5350±25    | Bos taurus          | 1 mace in the structure and another one between C1 and C2; 1 bifacial tool |
| 6      | simple corbeille | —     | —              | 5350±25    | Bos taurus          | 1 mace in the structure and another one between C1 and C2; 1 bifacial tool |
| 7      | simple corbeille | —     | —              | 5350±25    | Bos taurus          | 1 mace in the structure and another one between C1 and C2; 1 bifacial tool |
| 8      | simple corbeille | —     | 1 on the NE side | —          | —                   | —                        | —                                      |
| 9      | simple corbeille | —     | 1 central      | 5350±25    | Bos taurus          | 1 mace to the structure and 1 undecorated potsherd            |
| 10     | double ring corbeille | —     | 1 central      | 5400±30    | Bos taurus          | 2 bifacial tools          | —                                      |
| 11     | simple corbeille | —     | 1 central      | 5350±25    | undeterminable      | 1 pick                   | —                                      |
| 12     | complex corbeille | —     | 1 external     | —          | —                   | —                        | 1) undeterminable; 2) schematic bovid |
| 13     | simple corbeille | —     | 1 central      | —          | —                   | —                        | —                                      |
| 14     | simple corbeille | —     | 1 central      | 5350±25    | undeterminable      | —                        | —                                      |
| 15     | complex corbeille | —     | 1 collapsed    | 5660±30    | undeterminable      | —                        | —                                      |
| 16     | complex corbeille | —     | 1 central; 1 external (see below) | 5200±30    | Bos taurus          | —                        | —                                      |
| 16a    | standing stone | —     | external       | —          | Ovis vel Capra      | —                        | —                                      |
| 17     | stone structure | —     | —              | 1790±25    | undeterminable      | —                        | —                                      |
| 18     | complex corbeille | 6     | 9: 1 central; 1 for each annex; 2 external | 5490±30    | undeterminable      | —                        | —                                      |
| 19     | stone structure | —     | —              | —          | —                   | —                        | —                                      |
| 20     | complex corbeille | 1     | 1 central; 1 in the annex (see below) | 5340±40    | Ovis vel Capra      | —                        | 2 potsherds, rockers, plain edge (Middle Pastoral) |
| 20a    | standing stone | —     | external       | —          | Ovis vel Capra      | —                        | muzzles of two antelopes in profile of Pastoral style |


| Id   | Structure Type | Annex | Standing Stone | Age C14 BP | Fauna                        | Archaeological Materials | Rock art associated with the structure* |
|------|----------------|-------|----------------|------------|------------------------------|--------------------------|----------------------------------------|
| 22   | stone ring     | —     | —              | 2980± 25   | —                            | —                        | —                                      |
| 23   | stone platform | —     | —              | —          | —                            | —                        | —                                      |
| 24   | double ring corbeille | — | 1 central | 5520± 30 | Bos taurus, small ungulate | 2 maces                  | 2 potsherds, Alternately Pivoting Stamp (Middle Pastoral); | 1) a barely recognisable subject—probably an antelope |
| 25   | simple corbeille | —     | 1 central     | undeterminable | 1 mace close to the external perimeter | —                        | —                                      |
| 26   | complex corbeille | — | 1 central collapsed; 5 external | undeterminable | —                           | 6 potsherds, rocker plain edge (Middle Pastoral); 3 potsherds, Alternately Pivoting Stamp return tecnique (Middle Pastoral); 1 undecorated | —                                      |
| 26a  | area adjacent to the perimetral external wall | — | — | Bos taurus, Ovis vel Capra | — | — | |
| 27   | simple corbeille | —     | 1 collapsed   | —          | —                            | —                        | —                                      |
| 28   | stone ring     | —     | —              | small ungulate | —                           | —                        | —                                      |
| 29   | stone structure | —     | —              | —          | —                            | —                        | —                                      |
| 30   | simple corbeille | —     | 1 central     | 5400± 30   | Bos taurus, Ovis vel Capra | 1 mace                   | —                                      |
| 31   | deflated tumulus | —     | —              | —          | —                            | —                        | —                                      |
| 32   | stone structure | —     | 3 central     | —          | —                            | —                        | —                                      |
| 33   | simple corbeille | —     | —              | 5190± 30   | Equus sp., small ungulate   | —                        | 1) an elliptical shape (fish?); 2) four cattle vertically superimposed of Pastoral style |
| 34   | stone structure | —     | —              | —          | —                            | —                        | —                                      |
| 35   | stone ring     | —     | —              | —          | —                            | —                        | —                                      |
| 36   | stone structure | —     | —              | —          | —                            | —                        | —                                      |
| 37   | stone platform | —     | —              | 5750± 40   | Large ungulate               | —                        | —                                      |
| 38   | complex corbeille | —     | 1 central; 1 external (see below) | 5150±110 | Bos taurus, small ungulate | 1 mace                   | 32 undecorated potsherds; and 3 rocker plain edge decorated potsherds (Middle Pastoral); 1) an ovoid representation; 2) two superimposed cows of Pastoral style |
| 38a  | standing stone | —     | external       | 5290±40    | Bos taurus, small ungulate   | —                        | —                                      |
| 39   | simple corbeille | —     | 1 central     | 5380± 25   | Bos taurus                   | 2 maces inside the structure, 1 mace close to the external perimeter; 1 arrow head; 1 gouge | 34 potsherds (partially retting; rocker plain edge (Middle Pastoral); 1) schematic bovid; 2) ostrich of Pastoral style |
then ritually placed either in the structure, for example close to the
cattle head, or immediately outside the monument. At 07/110 C1,
where 3 maces were found, at least one was produced on the very
spot, probably to replace a broken one: façonnage flakes were placed
with the mace close to the animal head and a few could be refitted.
Other formal tools, including a grinding stone with traces of ochre
(07/55 C1), come from structures 00/301 (1 gouge), 07/79 C1 (2
bifacial knives), 07/110 C1 (1 arrow head, 1 gouge) and 09/69 C1
(1 bifacial tool).

Pottery is rare: only 9 structures yielded fragments of pots,
usually 1 or 2, with the exception of 00/557 (59) and 00/556 (35),
07/110 C1 (34) and 07/39 C2 (10), for a whole sample of 145
potsherds. Decoration is of the Middle Pastoral tradition, mostly
using a rocker stamp/plain edge technique or, less frequently, the
Alternately Pivoting Stamp (APS) one (see [65]). Undecorated
potsherds are also present. Only at 07/110 C1 the pot could be
partially refitted, showing a globular morphology and distinct neck
(Fig. 7). In all of the structures but one (07/39 C2), pottery sherds
were found in the lowest layers, next to the skull of the animal
(when present: 07/39 C3, 07/110 C1, 07/79 C1) or at the bottom
of the structure.

To summarize, stone maces represent the authentic emblem of
the complex gestures involved in the ritual slaughtering of the
animal. Their presence is signalled also in other monumental
structures, such as Tin Iblal [62] and most interestingly from the
Middle Pastoral quarrying site of In Habeter III [50]. Maces were

| Structure | Lab. Code | Material | Age uncal BP | Cal BC/AD | Cal BP | d13C, % |
|-----------|-----------|----------|--------------|-----------|--------|---------|
| 00/301    | GX-28456  | charcoal | 6080 ± 80    | 5216–4796 | 7165–6745 | −23.9   |
| 00/557    | GX-28448  | AMS      | 5750 ± 40    | 4703–4500 | 6652–6449 | −15.7   |
| 07/39 C6  | UGAMS 3760| charcoal | 5660 ± 30    | 4553–4374 | 6502–6323 | −10.19  |
| 00/300    | GX-28457  | AMS      | 5610 ± 40    | 4521–4356 | 6470–6305 | −17.3   |
| 07/55 C2  | UGAMS 5860| charcoal | 5590 ± 25    | 4462–4356 | 6411–6305 | −10.6   |
| 07/55 C1  | UGAMS 5859| charcoal | 5570 ± 25    | 4453–4355 | 6402–6304 | −25.3   |
| 07/39 C3  | UGAMS 3758| charcoal | 5520 ± 30    | 4450–4331 | 6399–6280 | −23.46  |
| 07/10 C1  | UGAMS 3756| charcoal | 5490 ± 30    | 4445–4262 | 6394–6211 | −11.51  |
| 07/39 C4  | UGAMS 2839| charcoal | 5430 ± 40    | 4355–4176 | 6304–6125 | −16.74  |
| 07/40 C1  | UGAMS 3761| charcoal | 5400 ± 30    | 4339–4085 | 6288–6034 | −25.86  |
| 07/79 C1  | UGAMS 3762| charcoal | 5400 ± 30    | 4339–4085 | 6288–6034 | −23.51  |
| 07/110 C1 | UGAMS 5853| charcoal | 5380 ± 25    | 4331–4076 | 6280–6025 | −24.1   |
| 07/68 C1  | UGAMS 5855| charcoal | 5350 ± 25    | 4321–4054 | 6270–6003 | −25.7   |
| 09/69 C1  | UGAMS 5856| charcoal | 5350 ± 25    | 4321–4054 | 6270–6003 | −27.8   |
| 07/28 C1  | UGAMS 5858| charcoal | 5330 ± 25    | 4245–4050 | 6194–5999 | −26.2   |
| 00/556 ext. st. | GX-28447| AMS | 5290 ± 40 | 4239–3992 | 6188–5941 | −12.6   |
| 08/01 C1  | UGAMS 3763| charcoal | 5220 ± 30    | 4223–3964 | 6172–5913 | −4.45   |
| 07/39 C5  | UGAMS 3759| charcoal | 5200 ± 30    | 4048–3960 | 5997–5909 | −13.92  |
| 07/39 C1  | UGAMS 3757| charcoal | 5190 ± 30    | 4044–3959 | 5993–5908 | −13.79  |
| 00/556 corb. | GX-2846| AMS | 5150 ± 110  | 4237–3707 | 6186–5656 | −10.9   |
| 07/40 SR17 | UGAMS 5854| charcoal | 2980 ± 25    | 1306–1126 | 3255–3075 | −25.6   |
| 07/40 SS22 | UGAMS 5857| charcoal | 1790 ± 25    | 134–325 AD | 1816–1625 | −25.0   |

*The quotation "BP" refers to uncalibrated years before present, according to Libby’s half-life. Calibration using OxCal online version 4.1 [85].

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most likely used to kill the animal(s)—or at least to give them the fatal, symbolic blow—and their systematic presence in monuments across several centuries supports the high formalization embedded in the ritual. The presence of fragments of pots strengthens the ritual value of the offerings, frequently deposed near the animal skull.

Analysis of faunal remains
Zooarchaeological analysis provided interesting insights on the rituals performed. Over 25,000 specimens were collected from 30 features belonging to 22 monuments. The distribution of the specimens in the different contexts is variable and only some of them yielded a significant number of identifiable remains (Tables 3 and 4; Text S1; Tables S5 and S6).

As far as species are concerned, 17 features contain cattle or large ungulates: in 6 cases *Bos taurus* was the only species recovered, in 3 others large ungulate was the only taxonomic category, while in 8 occurrences cattle is associated with ovicaprides or small ungulates. In these latter cases, however, small livestock is usually represented by few fragments, the only exception is structure 00/301 where *Ovis* vel *Capra* specimens are more abundant. Ovicaprines or small ungulate were the only taxon identified in 6 features. Structure 07/39 C1 yielded some equid specimens associated with very few small ungulates. In the last 5 features only unidentifiable fragments were recovered.

In most structures, for the main species a single individual is present (cattle, caprine or equid). The exceptions, with two *Bos*, are 07/40 C1 and 07/39 C3: in the latter, however, the single extra...
fragment may belong to the animal of 07/39 C2 external area, likely connecting the two monuments. Structure 00/301 with a minimum number of 2 cattle and 3 ovicaprine individuals represents an extreme outlier: here there seems to be also a differential distribution of cattle and small livestock in the various points of fire identified during the excavations. A similar differential distribution of species was found in 07/39 C5 where cattle remains were collected only in the corbeille and ovicaprines mainly under the external stele.

In most cases, the poor state of preservation of the bones prevented further assessments (sex, short-horn vs. long-horn, etc.) and only a few specimens could be measured (Table S5). Comparisons with available metric data from other sites in North Africa e.g., [26,66] show that the animals from the Messak were of similar size or slightly larger. The sex of Bos taurus, based of the size and morphology of metapodials, was tentatively attributed only for 4 animals, all males (Table 4): one of them is from 07/110 C1 where the close rock art engraving (Fig. 2) shows the sacrifice of a bull. A further example of this sexual selection is represented by the bull from In Habeter III [63]. The analysis of body part frequencies was achievable only for 18 features (Table S6). Cattle shows some variability: the skeleton is almost complete in 6 contexts; in five other cases the head (cranium and/or mandible) is preserved, sometimes associated with only few other elements. At 00/556 there seems to be a patterned distribution of the skeletal elements with the head placed in the corbeille and the long bones found at the basis of the external stele. Radiocarbon dates of the two samples, even if slightly different, have overlapping sigmas (Table 2). The cranial portions of the animal seem to have been important also at 07/39 C1 where the equid specimens were recovered. The anatomical pattern for the ovicaprines is usually less complete and standardized, except for structure 00/301 where almost all the skeleton is present. The only possible evidence for a selection of ovicaprine elements may occur at 07/39 C2 external area where 5 out of 4 identified specimens are humeri.

Only in a few cases it was possible to indicate the age at death of the animals (Table 4; see Text S1 for discussion). Except for structure 00/301 where cattle are less than 36 months old, the bovines are mainly adults, while the few ovicaprines tend to be younger. All the other individuals of the identified species could only generally be considered as “adults”.

Given the poor state of preservation of the assemblage, it was difficult to observe bone surface modifications. As a consequence, butchering traces are apparently very rare, but related to different stages of carcass processing, from skinning, disarticulation and defleshing to bone fracturing for marrow extraction.

A large proportion of the fragments was burnt: the incidence of fire damage on the bones is usually very high, often with many calcined specimens.

Differences were also observed in the location of these traces, in particular among the head portions. In structures 07/55 C1 and 09/69 C1 the presence of unburnt cranium, mandible as well as hyoid fragments may suggest that the cattle head was placed in the structure with soft tissues still attached. Differences in the frequency of burning were recorded also between cattle and ovicaprines when present in the same structure in significant numbers, as well as sometimes between the corbeille and the associated external stele.

Considering the available faunal data it is clear that, although with some variability and few exceptions, the ritual in this region was quite standardized. In most contexts domestic cattle played the main role with ovicaprines representing only a secondary species, as also suggested by the different treatment of the two animals (e.g., frequency of specimens, skeletal element representation, age, burning). The only real outlier is structure 00/301 where the rituals seem to involve in a similar manner Bos taurus and Ovis vel Capra, however such anomaly could be explained by the fact that this is the oldest structure analysed.

Age selection indicates that for cattle mainly adult individuals were chosen, while for the ovicaprines younger animals were preferentially killed. In other African sites [26,30], age data indicate slightly less mature animals. In the Messak, probably only bulls, rather than cows as in the case of some Egyptian and Niger sites, were selected for the sacrifice. The head of the animal was considered a relevant portion and was often placed at the bottom of the structure while, at least in some cases, the rest of the carcass was skinned, disarticulated and meat as well as marrow were
### Table 3. Faunal assemblage.

| Structure | Mollusca (Small Gastropoda) | Ostrich (egg shell) | Micromammals | Equus sp. | Ovis vel Capra | Bos taurus | Small Ungulate | Large Ungulate | Indeterminate | TOTAL | % BURNED |
|-----------|-----------------------------|---------------------|--------------|-----------|----------------|------------|----------------|----------------|---------------|--------|-----------|
| 00/301    | NR                          | NR                  | NR           | NR        | NR             | NR         | NR             | NR             | NR            | NR     | 100.0     |
| spot A    | 7                           | 7                   | 1            | 100.0     | 1242           | 57.7       |
| spot B    | 1                           | 261                 | 20           | 677       | 99.0           |
| spot C    | 3                           | 3                   | 40           | 95.2      |
| spot D    | 1                           | 15                  | 34           | 95.2      |
| other     | 3                           | 1                   | 3            | 95.2      |
| total     | 3                           | 1                   | 87           | 95.2      |
| 00/300    | 4                           | 1                   | 7            | 95.2      |
| 09/69 C1  | 131                         | 1                   | 95           | 66.2      |
| 07/28 C1  | 32                          | 1                   | 59           | 360       | 11.1          |
| 07/79 C1  | 75                          | 1                   | 115          | 2295      | 96.9          |
| 07/68 C1  | 83                          | 83                  | 0            | 0.0       |
| 08/01 C1  | 1                           | 1                   | 1            | 0.0       |
| 07/39 C6  | 1                           | 1                   | 3            | 75.0      |
| 07/39 C5  | corbeille                   | 5                   | 1            | 7         | 10.5          |
| ext.stele | 4                           | 2                   | 9            | 100.0     |
| total     | 5                           | 1                   | 5            | 7         | 22.7          |
| 07/40 SS2 | 4                           | 4                   | 5            | 25.0      |
| 07/10 C1  | 3                           | 5                   | 8            | 25.0      |
| 07/39 C4  | corbeille                   | 1                   | 14           | 12        | 31            | 58.1       |
| ext.stele | 1                           | 14                  | 62           | 77        | 98.7          |
| total     | 2                           | 1                   | 28           | 74        | 88.0          |
| 07/39 C3  | 164                         | 2                   | 145          | 4171      | 99.0          |
| 07/37 C1  | 2                           | 8                   | 10           | 30.0      |
| 07/39 C2  | corbeille                   | 17                  | 1            | 80.4      |
| ext. area | 4                           | 2                   | 49           | 550       | 80.4          |
| total     | 4                           | 2                   | 49           | 567       | 88.0          |
| 07/40 SR1 | 1                           | 16                  | 17           | 0         |
| 07/40 C1  | 6                           | 1                   | 159          | 3125      | 23.4          |
| 07/39 C1  | 7                           | 1                   | 2            | 3125      | 23.4          |
| 00/557    | 1                           | 2                   | 6            | 18        | 218           | 245        | 81.6          |
| 00/556    | corbeille                   | 3                   | 3            | 36        | 176           | 218        | 91.3          |
| ext.stele | 3                           | 3                   | 36           | 176       | 218           | 91.3       |
| total     | 1                           | 5                   | 9            | 54        | 394           | 463        | 86.2          |
consumed before the “leftovers” were collected and deposited in the monument after being intentionally burnt. Such intentionality is suggested in many contexts by the high frequency of calcined bones, which cannot be merely the result of cooking processes. On the basis of age and sex of the cattle, a large amount of meat was available (with the addition in some cases of the ovicaprines), suggesting that many people took part to the ritual. In a few structures (e.g., 00/301; 07/39 C2 and C3; 07/40 C1) more animals were slaughtered; this could be the evidence of special gathering places.

In other North African ritual sites with cattle bones the animal or parts of it are usually still articulated and burning is not a common occurrence e.g., [26,30,67]. Some similarities may be found with the so called “Tenerian meals” found in the Adrar Bous area [31], especially for the high incidence of burning, mainly on cattle elements, produced after consumption. However, there are dissimilarities in secondary species composition, number of individuals, anatomical representation as well as archaeological context.

The type of ritual identified in the Messak, although involving the same species of other North African areas, shows marked differences in the age and sex of the animals, as well as carcass treatment; they reflect the existence of a regional tradition, which given its level of standardization might have lasted over several centuries.

Isotope study

To have a measure of the environmental conditions in the area during the Pastoral phase and explore cultural phenomena linked to animal mobility we performed an isotope investigation on the animals buried in the stone monuments in the Messak and nearby areas. Animal stable isotope history was explored at the seasonal scale by means of sequential sampling of enamel along the tooth crown axis for carbon ($^13$C) and oxygen ($^18$O) isotope analysis [68], while local/exogenous origin and seasonal mobility were investigated through strontium isotope ratio ($^{87}$Sr/$^{86}$Sr) measured at the two furthermost oxygen values.

The state of preservation of the faunal remains was generally rather poor, we thus decided to sample only teeth in good conditions; out of 17, twelve came from the Messak (MK, respectively 10 of Bos taurus; 1 of Equus sp.; 1 of Ovis vel Capra), while 4 teeth were selected from the Edeyen of Murzuq (MQ, respectively 2 of Bos taurus; 1 of Ovis vel Capra; 1 of Hippopotamus amphibius), and 1 from the Erg Uan Kasa (UK, Bos taurus).

For strontium isotope analysis we collected 8 further specimens of terrestrial shells (Pupoides hogarensis) from the stone structures in the Messak: bulk readings could provide a measure of the local Sr isotope signature. While terrestrial shells are good indicators of the local geology, their association with the structures remains uncertain thus data should be considered with caution. Three samples of carbonate concretions from the nearby wadis were also collected. Bulk analysis of modern animal teeth from other areas (respectively 3 modern goat teeth–leftovers provided by local–from the area of Mathendous in the Messak and 2 teeth of Ammotragus lervia from carcasses found during our surveys in the Acacus Mountains) was performed as a further proxy of the local geology (see Fig. 1).

We excluded from our sampling burnt materials. The general poor state of preservation of the teeth only allowed the subsampling—for C and O isotope analysis—of 11 individuals from the Messak area (respectively 9 of Bos taurus, 1 of Equus sp. and 1 of Ovis vel Capra) and 2 from the Murzuq area (2 Bos taurus).
Table 4. Synoptic table of the faunal information available for the main structures.

| Structure / Feature | Main species | MNI (main species) | Sex | Other species (MNI & age) | Skeleton (main species) | Age teeth | Age post-cranium | Burning | Human modifications | Notes |
|---------------------|--------------|--------------------|-----|--------------------------|-------------------------|-----------|------------------|---------|---------------------|-------|
| 00/301 spot B       | Ovis vel Capra | 3                  | ?   | no                       | One almost complete, others few fragments. | 18–24 m   | 1:<10–16 m 1:<25–35 m 1:ca. 25–35 m | Total 57.7% Calcined 8.6% | no      | see notes 00/301 spot D |
| 00/301 spot C       | Bos taurus    | 1                  | ?   | no                       | Very few elements.     | n/a       | >18 m            | Total 99.0% Calcined 98.8% | 1 cut mark on a large ungulate rib shaft frag. | see notes 00/301 spot D |
| 00/301 spot D       | Bos taurus    | 2                  | ?   | Ovis vel Capra (MNI = 2; 1 is 18–24 m) | Bos one almost complete (only mandible present), other few fragments. Ovicaprine one relatively complete. | 18–24 m   | 2 <36 m          | Total 97.1% Calcined 95.1% 96.4% Bos & large ung. 73.2% Ovicaprine & small ung. Mandible burnt | 2 cuts on indetem. frgs, 1 scrape mark on a large ungulate rib, 1 chop mark on a small ungulate metapodial. |
| 09/69 C1            | Bos taurus    | 1                  | M   | no                       | Quite complete (right front limb absent?); phalanges almost completely missing. | 4–6 y (−4) | 2.5–3 y         | Total 66.2% Calcined 45.5% Cranium and mandible unburnt. | no | Cranium and mandible still articulated with soft tissues (and skin?) when buried? |
| 07/28 C1            | Bos taurus    | 1                  | ?   | no                       | No cranium, only mandible present; distal limb elements missing. | 8–10 y    | ~5 y            | Total 1.1% No calcined. Mandible unburnt. | Fresh bone fractures on a cattle humerus and on a large ungulate long bone shaft frag. |
| 07/79 C1            | Bos taurus    | 1                  | ?   | no                       | Largely incomplete.    | 4–6 y (~6) | 3.5–4.5 y       | Total 96.9% Calcined 13.0% Mandible burnt, cranium unburnt. | Disarticulation cut mark on a large ungulate rib. |
| 07/39 C5 corbeille & ext stele | Bos taurus    | 1 Bos + 1 Ovis vel Capra (stele) | ? | n/a                       | Very few elements for both species. | n/a       | "adults"       | Total 22.7% Calcined 15.2 Corbeille 10.5% Stele 100% | Cut mark on a small ungulate long bone shaft frag. |
| 07/39 C4 corbeille & ext stele | Ovis vel Capra | 1                  | ?   | no                       | Few elements, but from different parts of the skeleton. | n/a       | 18–26 m         | Total 88.0% Calcined 75.7% Corbeille 58.1% Stele 98.7% | Same individual deposited between corbeille and ext. stele? |
| 07/39 C3            | Bos taurus    | 1(+1?)             | M   | Small ungulate 2 frgs.   | Almost complete; humerus missing; a single extra metacarpal indicates second individual. | 4–6 y (~6) | 2.5–3 y         | Total 99.0% Calcined 98.4% Mandible burnt, cranium unburnt | The extra metacarpal of this individual may belong to the 07/39 C2 ext. area cattle. |
| Structure / Feature | Main species | MNI (main species) | Sex | Other species (MNI & age) | Skeleton (main species) | Age teeth | Age post-cranium | Burning | Human modifications | Notes |
|---------------------|--------------|--------------------|-----|--------------------------|-------------------------|-----------|-----------------|--------|--------------------|-------|
| 07/39 C2 ext.area   | Bos taurus   | 1                  | ?   | Ovis vel Capra (MNI = 2; 3 humeri, "adult") | Almost complete (left front limb absent!); mandible missing, but lower teeth present. | 4-6 y (~5) | 2.5-3.5 y | Total 80.4% Calcined 60.6% | Cranium and upper teeth burnt; lower teeth unburnt. | Two worked small ung. long bone shaft frgs.; a bone spatula on small ung. rib. Two large ung. long bone shaft frgs. with impact cone. Large ung. scapula blade with defleshing cut marks. |
| 07/40 C1            | Bos taurus   | 2                  | 1 M | Ovis vel Capra (MNI = 1; 18-24 m; few specimens) | One almost complete; only few elements of the front limb and a tooth indicate the presence of the second individual. | 7-9 y | 4.5-5 y | Total 23.4% Calcined 0.03% | Cranium and mandible burnt | Disarticulation cut marks on two ribs, a scapula and a pelvis of cattle. |
| 07/39 C1            | Equus sp.    | 1                  | ?   | Small ungulate 2 frgs. | Almost only upper teeth and mandible. | "adult" | n/a | Total 2.0% (all calcined) | Only a vertebra frg. burnt. Head elements unburnt. | no |
| 00/556 corbeille & ext.stele | Bos taurus | 1                  | ?   | Small ungulate 9 frgs. | Largely incomplete; cranium, mandible and teeth in platform post-cranium mainly in stele. | n/a | >24 m | Total 86.2% Calcined 84.4%Corbeille 81.6% Stele 91.3% Cranium burnt, mandible unburnt. | no | Same individual deposited between corbeille and ext. stele? |
| 07/110 C1           | Bos taurus   | 1                  | M   | no | Almost complete; lower teeth missing, but mandible present. | 4-6 y (~5) | 3-4 y | Total 63.2% Calcined 40.7% | Mandible burnt, cranium unburnt. | Skinning traces on a metatarsal and disarticulation traces on a rib, both of cattle. |
| 07/55 C1            | Bos taurus   | 1                  | ?   | no | Almost only cranium and mandible | 4-6 y (~6) | n/a | Total 6.7% Calcined 1.3% | Mandible and cranium unburnt. | Low incidence of burning may be explained by the scarcity of postcranial elements. Cranium and mandible still articulated with soft tissues (and skin?) when buried? |

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Table 5. Carbon ($\delta^{13}$C), oxygen ($\delta^{18}$O) and strontium ($^{87}$Sr/$^{86}$Sr) isotope ratio of tooth enamel bioapatite, carbonate rock and terrestrial shells from archaeological and modern specimens collected in the Libyan Sahara.

| Area code* | Sample ID | species/ material | tooth | sub-sample** | Mm from cej*** | $\delta^{13}$C-VPDB | $\delta^{18}$O-VPDB | $^{87}$Sr/$^{86}$Sr | % standard error |
|------------|-----------|-------------------|-------|--------------|---------------|----------------------|----------------------|-------------------|-----------------|
| MK 07/28 C1 | Bos taurus | M2 lower | 1 | 18 | $-2.0$ | $0.7$ |
| | | | 2 | 16 | $-0.7$ | $0.2$ |
| | | | 3 | 12 | 0.0 | 0.1 |
| | | | 4 | 10 | $-0.5$ | 0.6 |
| | | | 5 | 8 | $-0.6$ | 0.6 |
| | | | 6 | 4 | 0.3 | $-0.2$ |
| MK 07/79 C1 | Bos taurus | M3 upper | 1 | 28 | 1.5 | 2.7 |
| | | | 2 | 25 | 1.8 | 3.2 | 0.709748 | 0.00070 |
| | | | 3 | 21 | 2.3 | 2.1 |
| | | | 4 | 17 | 2.4 | 1.7 |
| | | | 5 | 13 | 2.2 | 0.9 |
| | | | 6 | 10 | 2.3 | 0.8 | 0.709717 | 0.00080 |
| MK 07/39 C3 | Bos taurus | P2 upper | 1 | 21 | 2.1 | 4.4 |
| | | | 2 | 19 | 2.4 | 4.2 |
| | | | 3 | 17 | 2.4 | 4.1 |
| | | | 4 | 15 | 2.5 | 4.3 | 0.709815 | 0.00060 |
| | | | 5 | 13 | 2.3 | 3.6 |
| | | | 6 | 11 | 1.9 | 2.9 |
| | | | 7 | 9 | 1.5 | 2.2 | 0.709814 | 0.00080 |
| | | | 8 | 7 | 1.1 | 2.9 |
| | | | 9 | 4 | 0.6 | 3.0 |
| | | | 10 | 2 | 0.3 | 3.9 |
| MK 07/39 C2 ext. | Bos taurus | M3 lower | 1 | 33 | $-5.9$ | $-1.0$ | 0.709715 | 0.00090 |
| | | | 2 | 29 | $-1.5$ | 2.1 | 0.709839 | 0.00070 |
| | | | 3 | 26 | $-1.2$ | 1.9 |
| | | | 4 | 23 | 0.1 | 2.1 |
| | | | 5 | 20 | 1.0 | 1.9 |
| | | | 6 | 17 | 2.4 | 1.6 |
| | | | 7 | 14 | 2.8 | 1.4 |
| | | | 8 | 11 | 2.7 | 0.6 |
| | | | 9 | 7 | 2.7 | 1.4 |
| | | | 10 | 3 | 3.4 | 0.6 |
| MK 07/40 C1(A) | Bos taurus | M1 upper | 1 | 8 | 2.2 | 0.9 | 0.709775 | 0.00070 |
| | | | 2 | 6 | 2.5 | 1.5 |
| | | | 3 | 4 | 2.3 | 1.7 | 0.709779 | 0.00070 |
| MK 07/40 C1(B) | Bos taurus | M1 upper | 1 | 5 | $-6.7$ | 4.0 | 0.709721 | 0.00060 |
| MK 07/39 C1 | Equus sp. | M3 upper | 1 | 5 | $-1.4$ | 2.8 | 0.708718 | 0.00070 |
| | | | 9 | | $-0.9$ | 0.8 | 0.709706 | 0.00070 |
| | | | 10 | | $-0.5$ | 1.1 |
| | | | 11 | | $-2.1$ | 1.0 |
| | | | 12 | | $-3.3$ | 1.5 |
| | | | 13 | | $-3.3$ | 0.9 |
| | | | 14 | | $-2.7$ | 1.2 |
| MK 00/556 corbeille | Bos taurus | fragment (M?) | | | | | | 0.709981 | 0.00080 |
| MK 00/556 corbeille | Small ungulate cf ovic | fragment | | | | | | 0.709671 | 0.00080 |
| Area code* | Sample ID | species/material | tooth | sub-sample** | Mm from cej*** | δ¹³C-VPDB | δ¹⁸O-VPDB | ⁸⁷Sr/⁸⁶Sr | % standard error |
|-----------|-----------|------------------|-------|-------------|----------------|-----------|-----------|----------|-----------------|
| MK        | 07/110 C1 | Bos taurus       | M3    | 1           | 36             | −2.7      | 1.0       |          |                 |
|           |           |                  |       | 2           | 34             | −3.4      | 1.9       |          |                 |
|           |           |                  |       | 3           | 31             | −3.4      | 2.2       |          |                 |
|           |           |                  |       | 4           | 28             | −3.6      | 2.5       |          |                 |
|           |           |                  |       | 5           | 26             | −3.2      | 2.6       |          |                 |
|           |           |                  |       | 6           | 23             | −2.7      | 2.4       |          |                 |
|           |           |                  |       | 7           | 20             | −1.7      | 2.7       | 0.709852 | 0.00080        |
|           |           |                  |       | 8           | 18             | −0.8      | 2.4       |          |                 |
|           |           |                  |       | 9           | 14             | 0.3       | 1.7       |          |                 |
|           |           |                  |       | 10          | 10             | 0.1       | 1.3       | 0.709667 | 0.00070        |
| MQ        | M4A/34    | Bos taurus       | M2    | 2           | 3              | −3.5      | 0.8       | 0.709975 | 0.00070        |
|           |           |                  |       | 3           | −3.7           | 1.1       |          |          |                 |
|           |           |                  |       | 4           | −2.6           | 1.5       |          |          |                 |
|           |           |                  |       | 5           | −2.5           | 1.9       |          |          |                 |
|           |           |                  |       | 6           | −2.5           | 2.2       |          |          |                 |
|           |           |                  |       | 7           | −1.4           | 2.2       | 0.709967 | 0.00060        |
|           |           |                  |       | 8           | 0.1            | 1.2       |          |          |                 |
|           |           |                  |       | 9           | 0.8            | 1.9       |          |          |                 |
|           |           |                  |       | 10          | 0.8            | 1.0       |          |          |                 |
| MQ        | M4/226    | Hippopotamus     |       |             |                | 0.709812  | 0.00070  |          |                 |
| MQ        | MT136     | Ovis vel Capra   | P2    |             |                | 0.709824  | 0.00080  |          |                 |
| MQ        | M4A/166   | Bos taurus       | M2    | 1           |                | 0.709873  | 0.00060  |          |                 |
|           |           |                  |       | 7           |                | 0.709853  | 0.00080  |          |                 |
| UK        | 94/75     | Bos taurus       |       |             |                | 0.711068  | 0.00070  |          |                 |
| MK        | #1 Wadi Bedis Carbonate concretion | 0.709538 | 0.00070  |
| MK        | #2 Wadi Mathendous Carbonate concretion | 0.709693 | 0.00080  |
| MK        | #3 Wadi Tullult Carbonate concretion | 0.709711 | 0.00070  |
| AC        | Ammo 1    | Ammotragus lervia | M2    | lower       |                | 0.710710  | 0.00070  |          |                 |
| AC        | Ammo 2    | Ammotragus lervia | M2    | lower       |                | 0.710656  | 0.00070  |          |                 |
|           | Libyan Modern Goat 1 Capra hircus | M2    | lower       |                | 0.710079  | 0.00080  |          |                 |
|           | Libyan Modern Goat 2 Capra hircus | M2    | lower       |                | 0.710171  | 0.00070  |          |                 |
|           | Libyan Modern Goat 3 Capra hircus | M2    | lower       |                | 0.709880  | 0.00070  |          |                 |
| MK        | 07/10 C1  | Pupoides hogarensis |      |             |                | 0.709701  | 0.00080  |          |                 |
| MK        | 07/10 C1  | Pupoides hogarensis |      |             |                | 0.709769  | 0.00080  |          |                 |
| MK        | 07/10 C1  | Pupoides hogarensis |      |             |                | 0.709764  | 0.00080  |          |                 |
| MK        | 07/39     | Pupoides hogarensis |      |             |                | 0.709675  | 0.00070  |          |                 |
| MK        | 07/28     | Pupoides hogarensis |      |             |                | 0.709707  | 0.00070  |          |                 |
| MK        | 07/28     | Pupoides hogarensis |      |             |                | 0.709612  | 0.00070  |          |                 |
| MK        | 07/110    | Pupoides hogarensis |      |             |                | 0.709680  | 0.00070  |          |                 |
| MK        | 00/556    | Pupoides hogarensis |      |             |                | 0.709623  | 0.00070  |          |                 |

*Area code: MK: Messak; MQ: Murzuq; AC: Tadrart Acacus; UK: Uan Kasa (see Fig. 1); ** Sub-sample no. refers to the sequential sampling of enamel along the tooth crown; *** abbreviations: cej = cement-enamel junction; M = molar; P = premolar.

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A general background of C, O and Sr isotope studies, together with methods of pre-treatment and analysis are included with the supplementary material (Text S1).

Only 9 teeth sequentially sampled for O and C isotope analysis yielded reliable results (respectively 7 Bos taurus and 1 Equus sp. from the Messak area and 1 Bos taurus from the Murzuq—the ovis caprines, mostly of young age, did not preserve enough enamel) (Table 3).

The δ13C values vary from −6.7 to 3.4‰ in bovine molars and premolars and from −3.3 to −0.5‰ in the equid molar. Excluding the very short sequences measured in 07/40 C1 individuals A and B, intra-tooth variability varies from 0.9‰ to 9.3‰ for δ13C and from 1.4 to 3.1‰ for δ18O in bovine teeth (Fig. 8). In the equid molar, intra-tooth variability is 2.9‰ for δ13C values and 2‰ for δ18O values. Within each sequence, the highest δ13C values occur shortly after the δ18O values reach their maximum, in agreement with what would be expected from the natural vegetation cycle, with a higher relative abundance of C4 plants and/or higher δ13C values for C1 plants in the dry season, and/or higher δ13C values for C1 plants in the wet one [69]. At these latitudes, with temperatures exceeding the amount effect threshold [70], the variations recorded in the δ18O values reflect seasonal variation in precipitation, with the highest δ18O values reflecting the dry season (winter), while in most sampled teeth, the wet (summer) season is truncated from the sequence, biasing the δ13C values recorded in tooth enamel towards dry season diet. The stable isotope sequences measured in the four bovine molars (07/39 C2 ext. area; 07/110 C1, 07/79 C1 and MA4/34) show very similar trends, with the highest δ18O and δ13C values occurring approximately at a distance from the enamel-root junction of 25 mm in the first case and 15 mm in the further three.

87Sr/86Sr ratios from the Messak area range between 0.70966 and 0.70998 for the bovine teeth, and 0.70971 and 0.70972 for the Equus, while the only sheep/goat sample has a signature of 0.70976. The bovine specimens from the area of Murzuq range between 0.70983 and 0.70998, with 0.70982 for the sheep/goat sample and 0.70981 for the hippopotamus. Hence, there is a substantial overlap in the Sr isotope signature from samples of the two areas. Significantly, the bovine specimen from the Erg Uan Kasa represents the only exception, with a Sr isotope signature of 0.71107 (Table 5). Mean Sr ratio of the terrestrial shells is 0.70968±0.00006, while the carbonate samples range between 0.70954 and 0.70971. Modern Sr isotope signature is not dissimilar to that of the prehistoric specimens: the two wild ruminants have comparable values that average 0.71068 while the dissimilar to that of the prehistoric specimens: the two wild ruminants have comparable values that average 0.71068 while the

39 C2 ext. area, 07/110 and 00/556) despite being local, cluster with the furthermost values of the local mean and group with the 39 C2 external area has the widest range of intra-tooth variation for δ13C values (9.5‰). In this tooth we measured the highest δ13C values of the sample (3.4‰) but also one of the lowest δ18O values (−5.9‰) suggesting a contribution of approximately 54% C3 plants to diet seasonally, this is also one of the individuals with greater variation in the Sr signal; the two proxies might suggest mobility between two diverse environments.

All animals from the Messak monuments appear to be feeding on similar geological substrates. When defining the local range using 2 times the standard deviation of the mean Sr isotope values of the ancient enamel samples [71], all cattle show a common ‘local’ origin (Fig. 9a). However, four individuals (07/39 C3, 07/39 C2 ext. area, 07/110 and 00/556) despite being local, cluster on the furthermost values of the local mean and group with the specimens from the Murzuq (Fig. 9a). The bovine sample from the Erg Uan Kasa falls outside both Messak and Murzuq ranges, which is unsurprising given the geological background of the area; the Sr signature of this single specimen appears more in line with those of humans of different Pastoral ages from the Wadi Tanezruft and Wadi Takarkori [18,39]. The signatures of modern goat samples are consistent or close to the geological background of the sample area even if, in two cases, they might reflect the contribution of imported fodder to the diet of these animals. The Ammotragus samples confirm an origin non-local to the Messak or Murzuq, and match that of the area of sampling (Acacus Mts.).

When combining δ13C and δ18O data with Sr isotope ratio, the picture becomes more integrated.

Similar trends in the sequences of δ18O and δ13C values in 07/39 C2 ext. area; 07/110 C1, 07/79 C1 and MA4/34 suggest these individuals were born at the same period of the year. Given that in extensive conditions, cattle breeding cycle is driven by environmental variables including the vegetation annual cycle [72], this would suggest that these individuals were born in areas similar at least from this point of view. Still, a great inter-individual variability in the range of δ13C values suggest they grazed on different pastoral areas. The latter seems to be confirmed, at least for individual 07/39 C2 ext. area and 07/79 C1, by the range of the Sr isotope signature at the furthest peaks of δ18O (dry vs. wet season) which appears to indicate that the bovines have moved between two geologically different areas (Fig. 9b). Unfortunately individual 09/69, which also suggests mobility, yielded unreliable C and O data.

Using a 14.1‰ isotope enrichment (ε) of δ13C between diet and enamel bioapatite [73], the δ13C values measured in the enamel were converted to diet δ13C values, leading to an estimation of the relative proportion of C3 and C4 plants in diet, using the mean values of −25.5‰ and −11‰ for pre-industrial C3 and C4 plants (see Text S1). Individuals may be grouped according to the relative proportion of C4 plants in their diet. 07/40 C1 individual B, although represented only by one value, is the only tooth that gave a δ13C value reflecting a C4 dominated signal (approximately 60% C4 in diet). In 07/39 C3, 07/79 C1, and 07/40 C1 individual A (represented only by three values), C4 plants are largely dominant (≥90%) to exclusive diet. These δ13C values are comparable to those measured in bovine teeth from low altitude modern and Neolithic (Elmenteitan) pastoral settlements in the savannah grassland of the Central Rift Valley in Kenya [74]. In 07/110 C1, MA4/34 and 07/28 C1, C4 plants dominate in diet, but a fair contribution of C3 plants is also detected seasonally (approximately 30–40%). This group of individuals gave similar range of δ13C values as the Equus. They may also be compared to δ13C values measured in cattle tooth enamel from historical and Elmenteitan occupations at higher elevation (2600 m) in the Central Rift Valley in Kenya, for which altitudinal mobility is suspected [74]. 07/39 C2 external area has the widest range of intra-tooth variation for δ13C values (9.5‰). In this tooth we measured the highest δ13C values of the sample (3.4‰) but also one of the lowest δ18O values (−5.9‰) suggesting a contribution of approximately 54% C3 plants to diet seasonally, this is also one of the individuals with greater variation in the Sr signal; the two proxies might suggest mobility between two diverse environments.

This great variability in the relative proportion of C3/C4 plants in the bovine diet is higher than what could be expected from individuals grazing in a single location and may suggest that these animals were coming from different places. Variability is also indicated by residue studies on potsherds from sites in the nearby Acacus Mountains [7]. We do not expect mean δ13C and δ18O values to be correlated in this sense (they are not), but would rather explain these different signals as reflecting diverse herding practices in terms of grazing areas, including location of pastures in altitude and possible seasonal mobility during the year to cope with variations in rainfall and other environmental constraints [34,35,38].

The Sr signature from all of the individuals [either Messak and Murzuq] is coherent with such a scenario, 87Sr/86Sr in most of the animals suggests a common origin. Within the Messak sub-sample, the 4 outliers fall within the Murzuq range. The integration of δ13C and δ18O data with the 87Sr/86Sr ratio outlines a picture of ‘local’ animals, mostly grazing on C4 plants though accessing
Figure 8. Carbon ($^{13}$C) and oxygen ($^{18}$O) data. Intra-tooth variation of carbon (solid diamonds) and oxygen (open diamonds) isotope ratios (in %) of enamel bioapatite of archaeological animals from the Messak and Murzuq. Abbreviations: $cej =$ cement-enamel junction. doi:10.1371/journal.pone.0056879.g008

Figure 9. Strontium isotope ratio ($^{87}$Sr/$^{86}$Sr) of archaeological and modern samples. (A) For both the Messak (dotted line) and Murzuq (dashed line) the local range is defined by 2 sd of the enamel mean values of the ancient animal samples. Intra-individual Sr signatures are measured at the two furthest oxygen values. Messak sample codes: 24 = 07/39 C3; 26a = 07/39 C2 ext.; 10 = 07/79 C1; 30(A) = 07/40 C1(A); 30(B) = 07/40 C1(B); 9 = 07/28 C1; 41 = 07/55 C1; 39 = 07/110 C1; 7 = 09/69 C1; 38 = 00/556. (B) Range of strontium isotope ratio ($^{87}$Sr/$^{86}$Sr) for the Messak and Murzuq animals. Abbreviations: MK = Messak; MQ = Murzuq; UK = Uan Kasa. doi:10.1371/journal.pone.0056879.g009
diversified pastures, likely in connection to intra-annual mobility between geologically consistent areas (along the wadis of the Messak and in the dunes of the Edyen of Murzuq).

The integration of δ13C, δ18O and 87Sr/86Sr data is particularly interesting for two structures (07/39 C3 with C2 external area and 07/40 C1). The two bovines in structure 07/39, even if hypothetically born at different times of the annual cycle show very different values, especially in the δ13C, so as to suggest different pastural areas. The discrepancy in the intra-individual mobility of the two animals, as reflected in the Sr isotope ratio supports this scenario.

Structure 07/40 C1 also contained two bovines, which were local as far as Sr isotope ratio is concerned, but despite having both very short δ13C and δ18O sequences, show rather different values hence different proportions of C3 and C4 plant contribution to their diet.

In both such cases a single structure or a single architectural context, host animals likely to thrive on different pastures or move at different scales of resolution. It is tempting to suggest that these animals might have been parts of different herds, which conveyed at a same area or were part of a same ritual.

**Archaeobotanical analyses**

To investigate possible plant accumulation in burials, a random set of botanical samples was taken from four well preserved monuments with *Bos taurus* bones, together with a few preserved and naked-eye visible remains of plants.

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**Figure 10. Percentage pollen diagram of three structures showing most of the identified pollen types.** Selected pollen sums (bottom) include the D (dry) and W (wet) sums, and pollen from plants living in water habitats.

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Pollen samples (structures 07/39 C3, 07/79 C1, 07/110 C1) were treated according to [75], and macroremains (structures 07/79 C1, 07/110 C1, 09/69 C1) were sorted under stereomicroscope (Text S1). The main results are reported in Table 6. Pollen flora is fairly similar in the different structures, showing prevalence of non arboreal pollen (NAP) and presence of tropical taxa (Fig. 10). Pollen spectra are dominated by the daisy family-Asteraceae (38% on average, 12 pollen types besides the undifferentiated Asteroideae) and by grass family-Poaceae (17%). Chenopods belonging to Chenopodiaceae/Amaranthaceae (6%), herbs of the carnation family-Caryophyllaceae (5%) and sedges-Cyperaceae (4%) are less represented. Plantains-Plantago and nettle family-Urticaceae are 3% each. Trees are low (7% on average) confirming that vegetation was open, and only fig tree-Ficus, toothbrush tree-Salvadora persica and tamarisks-Tamarix reach 1–1.5% on average. The sums of Asteraceae+Chenopodiaceae/Amaranthaceae (D) and Poaceae+Cyperaceae (W) indicate that the dry shrubland is almost always more represented than the savannah vegetation in the spectra. The D/W ratio is <1 only in sample p5 (structure 07/79 C1) as a result of the local abundance of grass pollen.

Seeds and fruits are well preserved in a desiccate state. Remains mainly consist of fruits of Rumex cyprius/vesicarius (cypriot dock/sorrel; Fig. 11) that amounts to 93% of the carpological record. Whole or fragmented fruits are preserved together with fruits (achenes) of Ficus and stem fragments of Poaceae in sample mc1, while other types of records are present in sample mc2. In structure 09/69 C1, only a few charred stems and twigs were found, while fruits were absent (Table 6).

Altogether, data show that the environments near the monuments were characterised by desert shrublands that periodically became brackish alternated with fresh-water habitats (especially at structures 07/79 C1 and 07/110 C1). Interestingly, the pollen list includes a significant number of tropical tree taxa (e.g., Balanites, Commiphora, Salvadora) spread in the Sahara during the mid-Holocene [76,77].

Inside structure 07/110 C1, a low concentration of microscopical organic matter, including that of pollen and charcoal particles, was observed. The sum of Plantago+Urtica pollen is 3.3%, and this is an indication of some trampling and frequentation around the monument [78]. A significant amount of Rumex cyprius/vesicarius was found in sample mc4, collected at 145 cm depth: given the exclusive presence within this level, we interpret this as evidence of an intentional deposition inside the burial.

Samples from the other two monuments, 07/39 C3 and 07/79 C1, contain more organic matter, probably related to a higher local accumulation of plants as flowers, fruits and charcoals. A relatively more intense frequentation around these two structures is signalled by the Plantago+Urtica sum (8.0–7.4%, respectively). In structure 07/79 C1, sample mc3 contains a very high amount of Rumex cyprius/vesicarius and, just below, sample mc2 shows the highest diversity of seeds/fruits in these deposits. In this monument, a special consideration for this plant is confirmed, though also other plants were collected.

On the basis of these data some palaeo-ethnobotanical inferences can be drawn. Burials have specific features that make their archaeobotany fairly different from that of settlements. Sometimes, distinctive pollen assemblages witness floral depositions and rituals, and mixed pollen spectra could reveal subsequent input of terrigenous material in burials e.g., [79]. According to [80], these contexts are particularly hard to interpret since samples

**Figure 11. Botanical remains.** Fruits of Rumex cyprius/vesicarius from structures 07/79 C1 (a, c = sample mc1; b, e = sample mc3) and 07/110 C1 (d = sample mc4). Record a still preserves the membranaceous parts of one wing; b has the remains of the wings, while records c and d lost their wings; d has still some purple colours in the remains of the veins (see detail).
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Table 6. Botanical samples and main results of microscopical analyses of pollen and plant macroremains.

| Structure | Age uncal. BP | Layer | Sample* | Sample location | Depth (cm) | Pollen concentration (p/g) | Results of analyses of pollen and macroremains** |
|-----------|---------------|-------|---------|----------------|------------|---------------------------|--------------------------------------------------|
| 07/39 C3  | 5520±30       | 3     | p 1     | inner area     | 38         | 2600                      | see description in 07/39 C3 sample p 4           |
|           |               | 4     | p 2     |                | 43         | 1500                      | see description in 07/39 C3 sample p 4           |
|           |               | 5     | p 3     |                | 45         | 3100                      | see description in 07/39 C3 sample p 4           |
|           |               | 6     | p 4     |                | 47         | 1000                      | Pollen from dry habitats, including 33% of Asteraceae, is high. Psammophilous habitats with Comosus, Ephedra and Molleopsis, which were not found in the other sites, are present. Plants from wet environments (4.0%) and Armeria (0.4%) are represented too. Tropical trees are represented by the Sudanian Balanites and Caesalpiniaeae (in p4), and the Sahelian Maerua (in p1) |
| 07/79 C1  | 5400±30       | 3     | mc 3    | below inner ring | 27         |                           | Rumex cypris/vesicarius (n. 400)                  |
|           |               | 2     | mc 2    | external ring  | 30         |                           | Rumex cypris/vesicarius (174 fruits); Ficus (19 fruits); Picris (9 fruits); Echium (1 fruit); Poaceae (10 stems and fragments; one floret of Pennisetum sp.); pods of Fabaceae (10); small flowers of Boraginiaeae (9) and thorns (4) |
|           |               | 2     | mc 1    | inner area    | 33         |                           | Rumex cypris/vesicarius (250 fruits); Ficus (5 fruits); Poaceae (fragments) |
|           |               | 7     | p 5     | inner area    | 44         | 3500                      | The lowest D/W sum is observed in this sample, especially because Asteraceae are 21%. Besides fresh-water habitats (14%), places with brackish water hosting Armeria (19%), and tamarisks on shores, are represented. The tropical-Sahelian Commiphora is exclusive. |
| 07/110 C1 | 5380±25       | —     | p 6     | eastern wall  | 184        | 830                       | see description in 07/110 C1 sample p 7          |
|           |               | —     | p 7     | eastern wall  | 214        | 730                       | Asteraceae, covering 59% of the spectra, testifies that drought-resistant shrubs and herbs grew near the site. The high value of Ficus observed in p6 (6.5%) is a local over-representation. Cassia and Combretum are example of the tropical taxa present in these deposits. Some evidence of local wet conditions is recognisable because the aquatic Potamogeton (0.9% on average) needs permanent water, here probably small mires, and the xerophilous Chenopods were not found. |
| 09/69 C1  | 5350±25       | 5     | mc 4    | stele pit     | 145        |                           | Rumex cypris/vesicarius (n. 46)                   |
|           |               | 6     | mc 5    | pit           |            |                           | few and small fragments of charred twigs and stems |

*p = pollen; mc = macroremains; ** Seeds/fruits are reported as number of records counted.
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The prevalence of herbaceous plant remains among the botanical samples is evident, indicating the presence of a diverse flora in the vicinity of the monuments. These plants, such as species of Rumex and Artemisia, are characterized by their rich reproductive structures, which were used for rituals and offerings. In the Messak, the botanical remains provide evidence of the ecological context of the monuments, reflecting the seasonal and environmental conditions of the time. The presence of Asteraceae pollen is particularly significant, as these plants are known for their attractive colors and are often associated with artistic expressions in rock art. This suggests a close connection between the use of plants and the religious or ceremonial practices associated with the monuments.

The analysis of the plant remains also reveals the use of wild plants in the diet, such as Rumex vesicarius, which is known for its medicinal properties and presence in arid environments. The seeds and fruits of this species were collected for their nutritional value and may have been used for offerings or as food for domesticated animals.

The combination of pollen and plant remains provides a comprehensive picture of the environmental context of the monuments. This information is crucial for understanding the relationship between human groups and their environment, as well as the specific practices associated with the monuments, such as the deposition of offerings and the performance of rituals. The multidisciplinary approach, integrating archaeological and palaeoecological methods, allows for a more nuanced understanding of the past, highlighting the complex relationships between humans and their environment in the Holocene Sahara.

Conclusions

The study of animal burials and plant remains in the Middle Pastoral monuments of the Messak provides evidence of a rich and enduring ritual tradition in the central Sahara. The presence ofofferings and the specialized procurement of plant material suggest the development of complex social and religious practices. The integration of isotopic data with palaeoecological analysis enhances our understanding of the environmental context and the timing of the rituals, as well as the movement of livestock and herders. This multidisciplinary approach is crucial for reconstructing the past and understanding the resilience of human groups in arid environments.

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Competing Interests

The authors have declared that no competing interests exist.
fruits may be related to their fragility, but their intrinsic characteristics—rarity, beauty, and medical properties—reflect the important value given to these plants.

Although it is impossible to archaeologically connect the rituals performed to specific ceremonial events (initiation, passage, wedding, transhumance, etc.), the gathering of different groups that involved feasting with the slaughtering of cattle might be considered a peculiar, distinct trait of Middle Pastoral herders. It would be fascinating to place these events at the end of the dry period, just before the transhumance from the Messak plateau towards the Murzuq lowlands, when the rainy season allowed the dispersal of these groups over a large area.

Even if the emergence of ritual burials of domestic cattle has been seen as a social response to deteriorating environmental conditions and expression of collective identity [33] or, alternatively, as material manifestation of ‘rain-making’ ceremonies and indicator of increasing complexity within Neolithic herders [21], it is its persistence and codification across the centuries to characterize this ritual as a specific ideological trait of Saharan pastoralists, as shown by the Middle Pastoral groups of the Messak: a potential, evocative analogue for the “African Cattle Complex” as known today.

Supporting Information

Text S1 Background, methods and supplementary data of the different disciplines.

Text S2 Survey in the Northern Messak Settatfet.

Table S1 Main features of the corbeilles, used for GIS analysis.

Table S2 Main features of the surveyed contexts in Northern Messak Settatfet.

Table S3 Database of the main rock art features, used for GIS analysis.

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Author Contributions

Directed the fieldwork: SDL. Coordinated and performed isotopic studies: MAT. Implemented GIS information and analysed rock art: MG. Studied the faunal remains and wrote the relevant parts of the paper: FA. Performed and interpreted Carbon and Oxygen analyses and wrote the relevant parts of the paper: MB. Performed pollen and botanical studies and wrote the relevant parts of the paper: AM. Performed strontium analysis: PF. Provided geomorphological data: AP AZ. Excavated and studied archaeological materials: LC MG AM. Conceived and designed the experiments: SDL MAT. Performed the experiments: SDL MAT MG FA MB PF AMM AM. Analyzed the data: SDL MAT MG FA MB AMM. Contributed reagents/materials/analysis tools: SDL MAT MG FA MB LC PF AMM AP AZ. Wrote the paper: SDL MAT MG.
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