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## Timing and pace of dairying inception and animal husbandry practices across Holocene North Africa

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### ABSTRACT

The timing and extent of the adoption and exploitation of domesticates and their secondary products, across Holocene North Africa, has long been the subject of debate. The three distinct areas within the region, Mediterranean north Africa, the Nile Valley and the Sahara, each with extremely diverse environments and ecologies, demonstrate differing trajectories to pastoralism. Here, we address this question using a combination of faunal evidence and organic residue analyses of c. 300 archaeological vessels from sites in Algeria, Libya and Sudan. This synthesis of new and published data provides a broad regional and chronological perspective on the scale and intensity of domestic animal exploitation and the inception of dairying practices in Holocene North Africa. Following the introduction of domesticated animals into the region our results confirm a hiatus of around one thousand years before the adoption of a full pastoral economy, which appears first in the Libyan Sahara, at c. 5200 BCE, subsequently appearing at c. 4600 BCE in the Nile Valley and at 4400–3900 BCE in Mediterranean north Africa.

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### 1. Introduction

A picture is now beginning to emerge of the widespread importance of dairying in the subsistence economies of Neolithic people. A combination of faunal and biomolecular evidence presently suggests that, in some instances, the adoption of dairying often occurs concurrently with the exploitation of domesticates, such as cattle, sheep and goats, albeit on varying scales of intensity and depending on local environmental, economic and cultural settings (e.g. Evershed et al., 2008). However, in other cases, such as in the Libyan Sahara, there seems to be a gap of at least one thousand years between the appearance of the earliest domesticates and the inception of dairying practices (di Lernia, 2013). Thus, it is increasingly becoming clear that the adoption and occurrence of dairying may have been a piecemeal process developing in varying ways (Evershed et al., 2008; Dunne et al., 2012; Debono Spiteri et al., 2016). Consequently, it is now recognised that what we see in the archaeological record reflects regional and

chronological variation in the appearance, spread and intensification of the different innovations.

#### 1.1. The secondary product revolution and lifetime products

It is now more than thirty years since Andrew Sherratt (1981, 1983) argued that, several millennia after the beginning of the development of animal husbandry, another innovation in animal exploitation occurred, involving the intensive use of secondary products such as milk, blood, wool and traction, which can be repeatedly extracted from an animal throughout its lifetime. There has been much debate, and some criticism, of Sherratt's model (e.g. Bogucki, 1982, 1984; Chapman, 1982; Whittle, 1985; see Greenfield, 2010 for a review and references therein) which has essentially crystallised over the timing of secondary product use. Nonetheless, Greenfield (2010) argues that Sherratt was always concerned with how and when the scale of exploitation changes and how this ultimately affected human society. He suggested that a distinction should be made between the first origins of dairying practices and the timing of its later intensification. Regardless, it now seems clear, from both organic residue analyses of absorbed residues from archaeological pottery and zooarchaeological techniques allowing

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the reconstruction of animal management practices, that the exploitation of secondary products begins with the first Neolithic farmers, supporting claims that milk was one of the main attractions leading to control/domestication (e.g. Vigne and Helmer, 2007; Evershed et al., 2008; Conolly et al., 2011). Interestingly, this provides valuable information regarding the sophisticated technological capabilities of 9th millennium BC herders. Although early milking may have been difficult, it seems the first farmers persevered, likely for the benefits it provided (Vigne and Helmer, 2007).

The importance of dairy foods in the diet of these early farmers should not be underestimated. Dairy foods are one of the most nutritionally dense foods, being significant sources of several nutrients, particularly calcium, riboflavin, phosphorus, protein, magnesium, vitamin B<sub>12</sub>, niacin equivalents, vitamin B<sub>6</sub>, and when fortified, vitamins A and D. Milk and milk products are also one of the main sources of dietary calcium which is highly important both in bone formation, and the maintenance of healthy bones and teeth. It also plays a role in the prevention, mitigation, and reversal of age-related decreases in bone density (Jensen, 1995). Yet, these early farmers are known to have been lactose intolerant, meaning the digestion of fresh milk would have caused extreme discomfort (Flatz and Rothauwe, 1977). However, certain methods of milk processing, such as fermentation, will reduce the lactose concentration (milk sugar) to lactic acid, making dairy produce more digestible to lactose intolerant people (Ingram et al., 2009). Hence, it seems likely that early farmers would have been able to produce a wide range of low-lactose, storable commodities through the processing of milk into products, such as butter, cheese and yoghurt, as observed in many modern-day societies.

It is also important to note the possible importance, among Holocene North African groups, of blood obtained from domesticates as a dietary resource. Today, the triad of milk, meat and blood common to pastoralist societies is well-documented (e.g. Evans-Pritchard, 1940; Holtzman, 2009). The consumption of blood is known to play a significant role in social relationships and is also an important source of dietary nutrients. However, although the use of blood would be difficult to identify archaeologically, it may well have its origins within these early pastoralist societies.

### 1.2. The identification of dairying practices

Analyses of absorbed organic residues from archaeological pottery, often combined with faunal osteo-archaeological age at death data, have provided direct evidence of the origins and transmission of dairying practices worldwide (e.g. Dudd and Evershed, 1998; Copley et al., 2003; Craig et al., 2005; Evershed et al., 2008; Dunne et al., 2012; Cramp et al., 2014a, 2014b; Smyth and Evershed, 2015; Debono Spiteri et al., 2016). Consequently, the identification of dairy and ruminant and non-ruminant carcass products from lipids extracted from ancient ceramics has revolutionised our knowledge of human diet and ancient economies (Evershed, 2008).

Herein, we explore the timing and spread of dairying in North Africa, a region where studies of organic residues are still rare. This is an area where, rather than the move from a mobile hunter-gathering to a sedentary farming lifestyle seen across the Near East and Europe, pathways to food production are very different. In contrast, across North Africa, generally semi-sedentary hunter-gatherer-fishers transition to more mobile pastoralist lifeways, likely in response to changing environmental conditions. In this study, questions of scale and intensity of milk production, both spatially and chronologically, will be addressed where possible, and the stable carbon isotopic values of the lipid residues will be used to infer animal management strategies and prevailing environmental

conditions.

### 1.3. Food production in north Africa

The existence of pastoralism as an established and widespread way of life in Africa, instead of the adoption of farming, and long before the domestication of plants, has been very hard for scholars to accept (e.g. di Lernia, 1999, 2013; Garcea, 2004, 2006; Gifford-Gonzalez, 2005; Barich, 2014) despite it being clear that the Near East model of 'Neolithisation' does not fit the model for the development of African subsistence strategies, which were likely shaped by the unstable, marginal environments that early Holocene Saharan hunter-gatherers lived in. Then, predictable access to resources would have been the major concern, rather than the intensification of yield more applicable to early farmers in the Levant (Marshall and Hildebrand, 2002). For example, in Saharan Africa, it seems that largely sedentary and pottery-producing hunters, fishers and gatherers quickly adopted the 'new' herding strategy, albeit dependent upon regional variations in climate and environment (di Lernia, 2013). Certainly, Marshall and Hildebrand (2002), among many others, have noted the 'patchy spread of food production' in Africa, where, in contrast to European prehistory, African hunter-gatherers and food producers (pastoralists, agriculturists) continued to co-exist (e.g. di Lernia, 1999, 2002, 2013; Hassan, 2002; Garcea, 2004; Gifford-Gonzalez, 2005; Barker, 2006; Linstädter, 2008; Marshall and Weissbrod, 2011; Linstädter et al., 2012a, 2012b; Lucarini, 2013). It is likely that spatial variation in climatic and environmental conditions, together with availability of food resources, dictated whether managing livestock or hunting took place. In addition, delayed use of food resources (Woodburn, 1982) by early Holocene foraging groups conceivably facilitated the adoption of the new herding strategy (di Lernia, 2001). Within this complex and varied mosaic of food production strategies, there are three distinct regions in North Africa, each of which follows its own pastoral trajectory. These areas comprise 1) Mediterranean north Africa including the Maghreb 2) The Nile Valley and the adjacent dry hinterlands and 3) Saharan Africa from west of the Nile to West Africa.

### 1.4. North African pastoral trajectories

Pastoralism spread unevenly from the northeastern corner of Africa to the Acacus (Libya) and Tibesti (Chad) massifs between c. 6500 and 4000 BCE and although early Holocene patterns of plant use persisted, Saharan pastoralists still hunted and fished (e.g. Smith, 1980; Gautier, 1987; Marshall and Hildebrand, 2002; di Lernia, 2013; Lucarini, 2014). The Sudanese Nile also offered reliable, fertile resources and pastoralists utilised large permanent camps such as Esh Shaheinab and Geili. Domesticates, predominantly cattle, were the dominant mammal at sites such as Kadero c. 4600 and 3800 BCE, where wild plants were again intensively exploited (Gautier, 1984; Caneva, 1988; Krzyzaniak, 1991; Haaland, 1992, 1995; Marshall and Hildebrand, 2002). The prehistory of Mediterranean north Africa follows a different trajectory although the cultural processes leading to the espousal of Neolithic innovations, such as the adoption of pottery and the exploitation of domesticates in the region, are still poorly understood. A simultaneous maritime spread of agriculture along the shores of the Western Mediterranean has been proposed, and as the adoption of a Neolithic lifestyle in both northern Morocco and south-western Spain is virtually contemporaneous, some contact and trading relationships between the two regions seems likely (Zeder, 2008; Linstädter et al., 2012b; Broodbank, 2013).

We now synthesise previously published evidence for the first dairying in Neolithic Saharan Africa (Dunne et al., 2012, 2013) and

from Mediterranean north Africa (Kherbouche et al., 2016) with new evidence from the Nile Valley. We present the results of a large-scale analysis of c. 300 potsherds from archaeological sites in Algeria (Gueldaman Cave), Libya (Takarkori rockshelter) and Sudan (Kadero), to produce a broad regional and chronological perspective on the uptake and subsequent intensification of dairy product exploitation across Holocene North Africa (Fig. 1a–d).

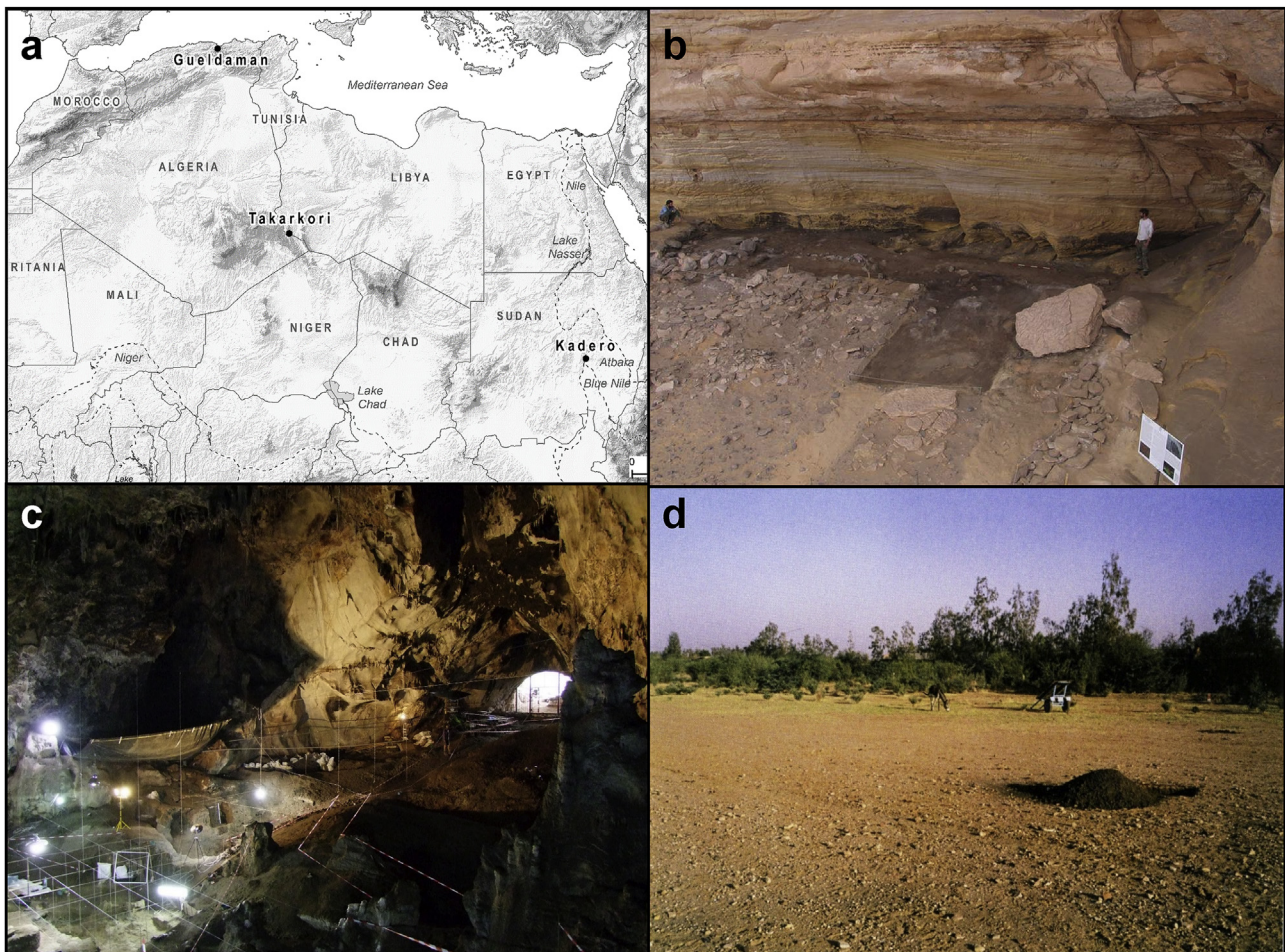
### 1.5. Diet and subsistence in the Neolithic of the Nile Valley

The early Holocene of the Nile Valley is characterised by a humid climate, but by the middle Holocene, the monsoon rainfall, and consequently, the vegetation and faunal zones, began to move southward, and the climate became drier (Wengrow et al., 2014). The pace and intensity of the monsoon withdrawal largely varied according to geographical and geomorphological features, with present-day desert conditions established across Northern Africa, including the Sahara, from approximately 3500 BCE (e.g. Kuper and Kröpelin, 2006). The human response to these environmental changes was to adopt a more mobile, pastoral lifestyle, exploiting the domesticated cattle, sheep and goat found throughout the Nile Valley from the fifth millennium BC (Table 1). These domestic stock were introduced from the Sahara (Haaland, 1992; Hassan, 1997), through a process of cultural contact with Saharan groups rather than large scale migration, evidenced by a continuity in pottery and lithic assemblages (Caneva, 1987, 1989; Marks and Mohammed-Ali,

1991; Haaland, 1995; Sadig, 2013). However, the Nile River and its close environs continued to offer more reliable, fertile resources, leading to pastoralists utilising mostly large permanent camps such as at Esh Shaheinab, Geili, el Kadada and Kadero located close to the Nile (Caneva, 1988; Krzyzaniak, 1991; Haaland, 1995).

The archaeological site of Kadero is situated north of Khartoum, some 17 km to the northeast of the junction of the White and Blue Nile (Fig. 1a and d). Kadero, identified as a permanent basecamp and used all year round (Tigani El Mahi, 1988), yielded the first direct evidence of a Neolithic pastoral economy in the region, that is, skeletal remains of domesticated animals such as cattle, sheep and goat. The site was occupied for around 1000 years (Table 1), from the first half of the fifth millennium to the beginning of the fourth millennium BC (4600–3800 BCE) and is attributed to the Early Neolithic (Krzyzaniak, 1991). However, it should be noted that the  $^{14}\text{C}$  chronology at Kadero is complex and not fully resolved. It seems likely that the site was occupied from around 5000 BCE, with occupation the most intensive between 4600 and 4000 BCE (Chłodnicki, pers. comm).

The faunal assemblage included c. 36,000 bone fragments; and although fragmentary, the preservation was good. Domestic cattle, including horn core remains, skull fragments and large amounts of postcranial remains form the majority of the collection (87%,  $n = 1526$ ), followed by sheep and goat (13%,  $n = 228$ ) with sheep being three times as abundant as goat. In comparison to livestock (81%), game comprises 19% of the assemblage, suggesting that



**Fig. 1.** a. Map of North Africa and images of the three sites sampled, b. Takarkori rockshelter, Libya, c. Gueldaman Cave, Algeria and d. Kadero, Sudan. Image a/b. © The Archaeological Mission in the Sahara, Sapienza University of Rome.

**Table 1**  
Site age range, cultural phase, age of adoption of domesticates and age/percentage of dairying.

Site	Selected $^{14}\text{C}$ dates	Site age range	Cultural phase	Age of adoption of domesticates (at site)	Age/percentage of dairying
Kadero, Sudan	KN-2822: 5610 $\pm$ 55 cal BP, 4500–4380 BCE GD-5648: 5720 $\pm$ 50 cal BP, 4650–4500 BCE GD-5652: 5420 $\pm$ 70 cal BP, 4350–4080 BCE GD-5651: 5370 $\pm$ 60 cal BP, 4300–4075 BCE	4600–3800 BCE	Early Neolithic	4600 BCE	4600 BCE 47%
Takarkori, Libya	LTL914A 7327 $\pm$ 65 (8320–8000 cal BP), 6370–6060 BCE GX-31064 7130 $\pm$ 100 (8180–7750 cal BP), 6230–5800 BCE UGAMS#01842 6230 $\pm$ 90 (7420–6890 cal BP), 5470–4940 BCE GX-30324-AMS 6090 $\pm$ 60 (7160–6790 cal BP), 5210–4840 BCE GX-31077 5600 $\pm$ 70 (6550–6280 cal BP), 4600–4330 BCE UGAMS#8707 4970 $\pm$ 25 (5750–5610 cal BP), 3800–3660 BCE	6370–4940 BCE 5210–3660 BCE	Early Pastoral Middle Pastoral	6370–6100 BCE	Not Known 5200 BCE 50%
Guedaman, Algeria	SacA29728: 5995 $\pm$ 40 (6835 cal BP), 4991–4791 BCE SacA41908: 6130 $\pm$ 35 (7022 cal BP), 5200–4900 BCE SacA29730: 5280 $\pm$ 30 (6073 cal BP), 4200–4000 BCE SacA29727: 5210 $\pm$ 30 (5961 cal BP), 4100–3900 BCE	5000–4900 BCE (UA1) 4400–3900 BCE (UA2) 3000 BCE (UA3)	Early Neolithic (UA1) Middle Neolithic (UA2 & UA3)	5000–4900 BCE	5000–4900 BCE 5% 4400–3900 BCE 38%

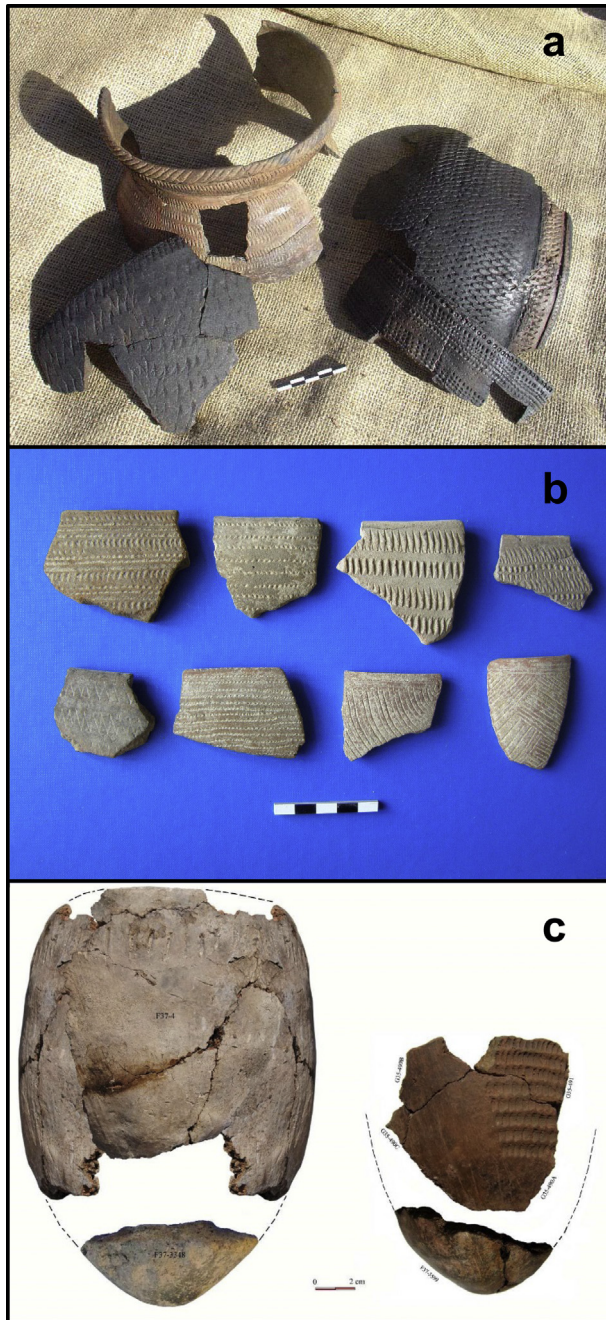
some hunting of wild mammals, i.e. antelopes, gazelle, giraffe and hippopotami, remained part of the subsistence strategy of the inhabitants of the site (Gautier and Van Neer, 2011).

Lipid analysis and interpretations were performed using established protocols described in detail in the methods section, supplementary information (Dudd and Evershed, 1998; Copley et al., 2003; Correa-Ascencio and Evershed, 2014; Kherbouche et al., 2016). A total of 80 Early Neolithic potsherds from Kadero were analysed using GC, GC-MS and GC-C-IRMS (Fig. 2b, Table 2 and Table 3, supplementary information). Lipid biomarker analyses by GC-MS showed the Kadero residues to fall into 2 broad categories. Of these,  $n = 10$  (40%) yielded high abundances of  $\text{C}_{16:0}$  fatty acid but relatively much lower abundances of  $\text{C}_{18:0}$  fatty acid, a distribution indicative of a plant origin. These residues also comprised sequences of even-numbered long-chain fatty acids, containing  $\text{C}_{20}$  to  $\text{C}_{28}$  acyl carbon atoms, common in the epicuticular waxes of plants (Tulloch, 1976). Together the overall fatty acid compositions suggest these residues are likely of plant origin and thus these were not selected for  $\delta^{13}\text{C}$  analysis. Residues unambiguously assigned as degraded animal products ( $n = 15$ , 60%; Fig. 3b), i.e. those where the  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  fatty acids predominated, were selected for GC-C-IRMS analysis to determine the  $\delta^{13}\text{C}$  values for the individual  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  carboxylic acids. The  $\delta^{13}\text{C}$  values of the  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  fatty acids reflect their biosynthetic and dietary origin, allowing non-ruminant and ruminant adipose and ruminant dairy products to be distinguished (Dudd and Evershed, 1998; Copley et al., 2003; Dunne et al., 2012).

Of these, 47% plotted within, or on the edge of, the isotopic ranges for dairy products (Fig. 4e), sometimes displaying more negative  $\Delta^{13}\text{C}$  values than normally seen, a trend seen in environments where  $\text{C}_4$  plants predominate (Table 2). These data confirm the exploitation of domesticated animals and their secondary products was taking place at this Nile Valley site in the fifth millennium BC. Of the remainder, two plot within the range for ruminant carcass products, five plot within the non-ruminant carcass products and a further one plots between the ranges for ruminant and non-ruminant products, possibly suggesting some mixing of domesticated and hunted animal products.

The range and distribution of the  $\delta^{13}\text{C}$  values from Kadero is exceptional (Table 2), with the  $\delta^{13}\text{C}_{16:0}$  values ranging from  $-26.5$  to  $-13.7\text{‰}$  ( $-12.8\text{‰}$  difference) and from  $-29.2$  to  $-14.0\text{‰}$  for the  $\delta^{13}\text{C}_{18:0}$  ( $-15.2\text{‰}$  difference), although these cluster within two distinct groups, suggesting that the animals producing these fats consumed diets which comprise primarily  $\text{C}_3$  (generally found in more temperate regions) or  $\text{C}_4$  (arid adapted) plants. The  $\Delta^{13}\text{C}$  values, ranging from  $-8.2$  to  $7.4\text{‰}$  (Fig. 4e), demonstrates the broadest spread yet seen from archaeological lipid extracts, although values like this have been seen in reference fats i.e.  $-7.1\text{‰}$ , (Salque, 2012). The interpretation of these residues is complex but some interesting trends can be observed, for example, the extracts displaying the most positive  $\Delta^{13}\text{C}$  values have a  $\text{C}_3$  origin and conversely those with the most negative values a  $\text{C}_4$  origin, as judged by the  $\delta^{13}\text{C}_{16:0}$ . The residues with  $\delta^{13}\text{C}$  values denoting a  $\text{C}_4$  dietary component mostly plot in the dairy range but with one value in the ruminant adipose range and the other in the non-ruminant range. It is interesting that the animal products with a dairy origin predominantly originate from animals subsisting on a wholly  $\text{C}_4$  plant diet, possibly suggesting specific animal management practices. However, a note of caution should be sounded here as it is known that isotopic variations in plants, incorporated into the tissues of animals consuming them, can result from seasonal shifts or differences in habitat composition (Cerling and Harris, 1999; Heaton, 1999; Codron et al., 2005, 2013; Dungait et al., 2008; di Lernia et al., 2013; Roffet-Salque et al., 2016a).

Gautier and Van Neer (2011) argued that, although the site's inhabitants were living a settled lifestyle, some transhumance may have taken place, moving the cattle between the alluvial plain and the hinterland. Certainly, the local environment comprised a broad range of ecosystems, including the river and terraces (Kobusiewicz, 2011), the area around the site which comprised dry shrub and thorn (Barakat, 1995) and the savannah in the hinterland, which included stands of wild grasses. However, if some transhumance was taking place, it might be expected that the  $\delta^{13}\text{C}_{16:0}$  values would show more variation across the span, similar to the Takarkori residues, rather than being clustered into two distinct groups. Rather, the lipid profiles from Kadero suggest two different types of



**Fig. 2.** Potsherds and partially reconstructed vessels from the three sites sampled, a. Takarkori rockshelter, Libya, b. Kadero, Sudan and c. Gueldaman Cave, Algeria.

animal product processing are seen in these vessels. The residues with the enriched ( $C_4$ )  $\delta^{13}C$  values and negative  $\Delta^{13}C$  values,  $n = 6$ , mostly plot in the dairy range, but with two residues in the ruminant adipose range and the other lying on the border between ruminant adipose and non-ruminant (wild fauna) range (Fig. 4e). Those with  $\delta^{13}C$  values denoting a  $C_3$  origin (and most positive  $\Delta^{13}C$  values) largely plot in the non-ruminant (wild fauna) range. This implies that the dairy product residues originate from cattle eating a wholly  $C_4$  diet, perhaps as a result of an animal husbandry strategy which involved the animals grazing on, or being foddered by, the stands of wild  $C_4$  grasses found on the savannahs close to the site. Certainly, cattle, the dominant species at the site, are known to eat wild sorghum and other  $C_4$  grasses (Snow, 1948). Analysis of

plant impressions found on pottery at the site documents the presence of mainly wild sorghum (*Sorghum bicolor* ssp. *Arundinaceum*) and other grasses from the wild millet group (*Setaria*) and the use of wild sorghum as food throughout the eastern Sahara is archaeologically well-documented (Stemler, 1990; Wasylikowa et al., 1995; Barakat and Fahmy, 1999; Wasylikowa and Dahlberg, 1999; Kubiak-Martens, 2011). The other distinctive profile suggests some exploitation of wild fauna, which are subsisting on more  $C_3$  diets. As noted, the presence of wild species in the faunal assemblage suggests some hunting remained part of their subsistence economies.

The faunal assemblage at the site comprised mainly domestic cattle (87%,  $n = 1526$ ), followed by sheep and goat (13%,  $n = 228$ ) with sheep being three times as abundant as goat. Interestingly, kill-off patterns show that twice as many young sheep and goat than adult, or nearly adult, were slaughtered. This proportion was 2:3 for cattle. Furthermore, more young sheep and goat were slaughtered than cattle, suggesting small livestock were more readily sacrificed than large livestock, a strategy which makes economic sense if only restricted quantities of meat are required (Gautier and Van Neer, 2011). This correlates well with the lipid residues which suggest that dairying was of much greater economic importance. Unfortunately, it is not known whether those slaughtered were male animals, which might imply that females were kept for milk production. However, retaining more adult cattle than sheep or goat suggests that it was the cattle that were preferentially retained for milking.

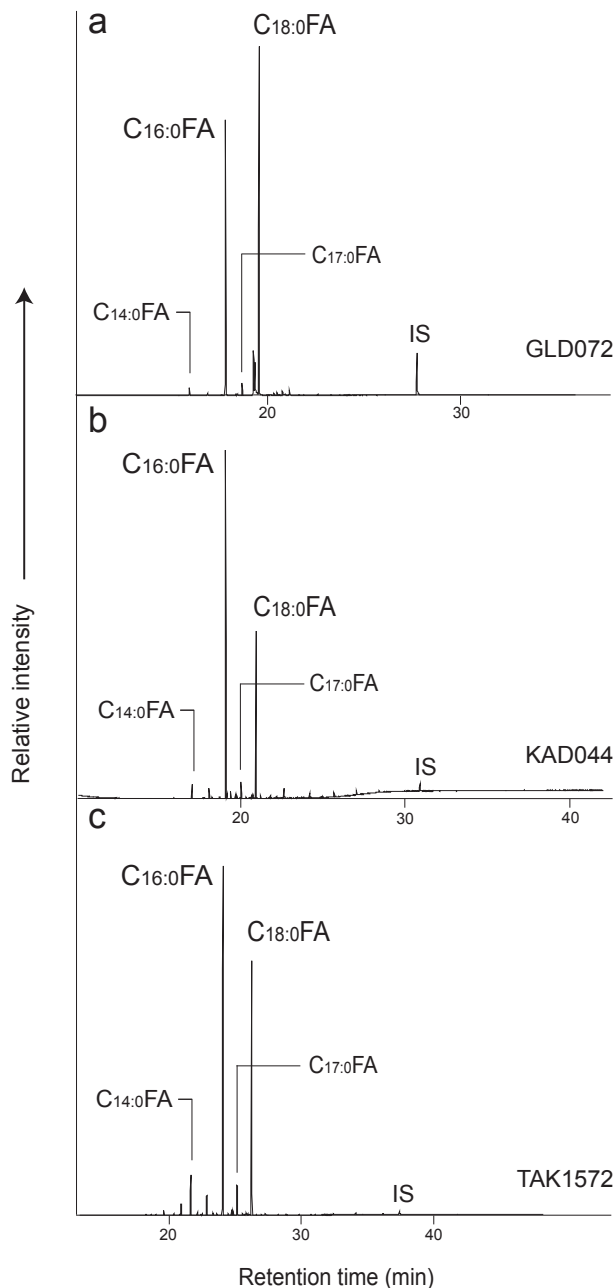
#### 1.6. Diet and subsistence in the Mediterranean Neolithic

In recent years, several research projects investigating the pre-history of Mediterranean north Africa have added significantly to our understanding of the region (e.g. Linstädter, 2003; Barker et al., 2008, 2012; Jackes and Lubell, 2008; Linstädter et al., 2012a; Linstädter and Kehl, 2012; Lucarini, 2013; Morales et al., 2013; Mulazzani, 2013; Zoughlami, 2013; Belhouchet et al., 2014; Jackes and Lubell, 2014; Kherbouche et al., 2014; Lubell, 2014; Mulazzani, 2014; Morales et al., 2015; Linstädter et al., 2016; Lubell, 2016; Mulazzani et al., 2016). However, our knowledge of the geographic extent and chronology of the Mediterranean north African Neolithic, and of the cultural processes leading to the adoption of Neolithic innovations, including the exploitation of domesticates, is still fragmentary (Linstädter, 2008; Lucarini, 2013; Lubell, 2014; Mulazzani et al., 2016). In the eastern Maghreb, the Capsian period, denoted by broad-spectrum hunting and gathering strategies, ends late, at around 5000 BCE. The Capsian culture is followed by the Neolithic of Capsian tradition (*Néolithique de Tradition Capsienne*) although the extent to which Neolithic economic practices are adopted by the later Capsian groups is not fully understood (Roubet, 2001; Rahmani, 2004; Linstädter, 2008). However, recent work at Tunisian sites (SHM-1 and KH) suggests Capsian foragers adopt selected features of the 'Neolithic' package, based on economic intensification, garnered from multiple influences (Mulazzani et al., 2016). Furthermore, at the site of Grotte Capéletti in the Aurès Mountains, Algeria, c. 5800–4800 BCE, the inhabitants practised transhumance as part of a pastoral lifestyle, exploiting domesticated cattle, sheep and goats (Roubet, 2001, 2003; Lubell et al., 2009).

Consequently, the rich and diverse archaeological record uncovered during recent excavations at Gueldaman Cave, Algeria (Fig. 1a and c), located on a ridge situated in the western Tellian Babors, demonstrates its potential as a key site for helping to understand the North west African Neolithisation process (Kherbouche et al., 2014, 2016; Merzoug et al., 2016). The well-preserved faunal assemblage also meant the lipid residue results,

**Table 2**  
Details of sherds,  $\delta^{13}\text{C}_{16:0}$ ,  $\delta^{13}\text{C}_{18:0}$ , and  $\Delta^{13}\text{C}$  values and classification of residues from potsherds from Gueldaman (GLD), Algeria; Takarkori (TAK), Libya and Kadero (KAD), Sudan.

Sherd number	Period	$\delta^{13}\text{C}_{16.0}$	$\delta^{13}\text{C}_{18.0}$	$\Delta^{13}\text{C}$	Classification
TAK30	Late Acacus	-13.9	-13.8	0.1	Non-ruminant adipose
TAK32	Late Acacus	-19.3	-17.5	1.8	Non-ruminant adipose
TAK21A	Middle Pastoral	-14.7	-20.5	-5.8	Dairy Fat
TAK1	Middle Pastoral	-14.2	-15.0	-0.9	Ruminant adipose
TAK120	Middle Pastoral	-15.2	-18.7	-3.5	Dairy Fat
TAK124	Middle Pastoral	-18.1	-20.1	-2.0	Ruminant adipose
TAK420	Middle Pastoral	-18.3	-21.5	-3.2	Dairy Fat
TAK443	Middle Pastoral	-16.9	-23.7	-6.8	Dairy Fat
TAK9	Middle Pastoral	-13.7	-19.0	-5.2	Dairy Fat
TAK873	Middle Pastoral	-18.5	-17.7	0.8	Non-ruminant adipose
TAK987	Middle Pastoral	-13.6	-19.3	-5.7	Dairy Fat
TAK15	Middle Pastoral	-13.3	-17.4	-4.1	Dairy Fat
TAK1009	Middle Pastoral	-11.0	-11.0	0.0	Non-ruminant adipose
TAK1012	Middle Pastoral	-14.9	-16.5	-1.7	Ruminant adipose
TAK25	Middle Pastoral	-15.6	-19.7	-4.1	Dairy Fat
TAK29	Late Pastoral	-18.5	-19.7	-1.2	Ruminant adipose
TAK21	Late Acacus	-23.1	-19.8	3.3	Non-ruminant adipose
TAK24	Early Pastoral	-21.9	-21.0	0.9	Non-ruminant adipose
TAK27	Early Pastoral	-22.8	-21.7	1.1	Non-ruminant adipose
TAK45	Middle Pastoral	-21.9	-24.1	-2.1	Ruminant adipose
TAK197	Middle Pastoral	-20.9	-21.1	-0.2	Non-ruminant adipose
TAK6	Middle Pastoral	-22.0	-21.7	0.3	Non-ruminant adipose
TAK896	Middle Pastoral	-23.6	-25.0	-1.5	Ruminant adipose
TAK1572	Middle Pastoral	-23.7	-28.2	-4.5	Dairy Fat
TAK26	Middle Pastoral	-22.3	-26.2	-4.0	Dairy Fat
TAK2028	Middle Pastoral	-24.5	-28.9	-4.4	Dairy Fat
TAK28	Middle Pastoral	-21.5	-24.0	-2.5	Ruminant adipose
TAK35	Middle Pastoral	-20.1	-22.9	-2.8	Ruminant adipose
TAK11	Late Pastoral	-20.5	-24.9	-4.4	Dairy Fat
GLD032	Middle Neolithic	-27.0	-27.6	-0.5	Mixed ruminant and non-ruminant adipose
GLD035	Middle Neolithic	-27.3	-33.2	-5.9	Dairy fat
GLD038	Middle Neolithic	-26.7	-31.7	-5.0	Dairy fat
GLD039	Middle Neolithic	-28.0	-29.8	-1.9	Ruminant adipose
GLD041	Middle Neolithic	-27.1	-26.8	0.2	Non-ruminant adipose
GLD043	Middle Neolithic	-28.1	-26.9	1.2	Non-ruminant adipose
GLD044	Early Neolithic	-28.3	-28.4	-0.1	Mixed ruminant and non-ruminant adipose
GLD056	Middle Neolithic	-26.3	-30.6	-4.3	Dairy fat
GLD062	Middle Neolithic	-27.3	-30.5	-3.2	Mixed dairy and adipose fat
GLD072	Early Neolithic	-26.9	-27.7	-0.8	Ruminant adipose
GLD075	Early Neolithic	-27.6	-28.8	-1.2	Ruminant adipose
GLD077	Early Neolithic	-27.5	-28.8	-1.2	Ruminant adipose
GLD079	Early Neolithic	-27.4	-28.4	-1.0	Ruminant adipose
GLD081	Early Neolithic	-26.9	-27.6	-0.7	Ruminant adipose
GLD089	Early Neolithic	-22.4	-25.5	-3.2	Mixed dairy and adipose fat
GLD091	Early Neolithic	-27.8	-28.3	-0.5	Mixed ruminant and non-ruminant adipose
GLD098	Early Neolithic	-25.9	-27.9	-2.0	Ruminant adipose
GLD103	Early Neolithic	-27.0	-28.7	-1.7	Ruminant adipose
GLD104	Early Neolithic	-26.3	-28.3	-2.0	Ruminant adipose
GLD105	Early Neolithic	-26.4	-28.1	-1.7	Ruminant adipose
GLD112	Early Neolithic	-27.4	-31.5	-4.1	Dairy fat
GLD114	Early Neolithic	-25.5	-27.0	-1.5	Ruminant adipose
GLD118	Early Neolithic	-26.7	-28.5	-1.8	Ruminant adipose
GLD121	Early Neolithic	-26.2	-27.4	-1.2	Ruminant adipose
GLD122	Early Neolithic	-26.9	-27.3	-0.4	Mixed ruminant and non-ruminant adipose
GLD125	Early Neolithic	-27.9	-28.9	-1.0	Ruminant adipose
GLD130	Early Neolithic	-25.1	-25.5	-0.4	Mixed ruminant and non-ruminant adipose
GLD146	Early Neolithic	-24.7	-27.3	-2.6	Ruminant adipose
KAD004	Early Neolithic	-13.9	-16.5	-2.6	Ruminant adipose
KAD013	Early Neolithic	-17.3	-25.5	-8.2	Dairy Fat
KAD017	Early Neolithic	-15.9	-22.0	-6.1	Dairy Fat
KAD018	Early Neolithic	-14.8	-18.1	-3.4	Dairy Fat
KAD028	Early Neolithic	-14.1	-14.0	0.1	Non-ruminant adipose
KAD031	Early Neolithic	-25.7	-20.4	5.3	Non-ruminant adipose
KAD032	Early Neolithic	-24.3	-16.9	7.4	Non-ruminant adipose
KAD033	Early Neolithic	-25.2	-20.5	4.7	Non-ruminant adipose
KAD034	Early Neolithic	-24.9	-25.3	-0.4	Non-ruminant adipose
KAD035	Early Neolithic	-25.3	-29.2	-3.8	Dairy Fat
KAD036	Early Neolithic	-26.5	-24.1	2.4	Non-ruminant adipose
KAD037	Early Neolithic	-15.3	-19.4	-4.1	Dairy Fat
KAD040	Early Neolithic	-18.2	-25.3	-7.1	Dairy Fat
KAD043	Early Neolithic	-13.7	-19.5	-5.9	Dairy Fat
KAD044	Early Neolithic	-19.3	-21.3	-2.0	Ruminant adipose



**Fig. 3.** Partial gas chromatograms of trimethylsilylated total lipid extracts (TLEs) from a. Gueldaman, Algeria (GLD072), b. Kadero, Sudan (KAD044) and c. Takarkori rock-shelter (TAK1572). FAx are fatty acids where x is the carbon chain length; IS, internal standard, *n*-tetratriacontane (*n*-C<sub>34</sub>).

demonstrating animal products processing, could be directly correlated with archaeozoological reconstructions of animal management practices (i.e. kill-off patterns). Both these techniques can be used as complementary pieces of evidence regarding dietary practices, herding strategies and, on occasion, species-specificity (Vigne and Helmer, 2007; Evershed et al., 2008; Salque et al., 2012; Debono Spiteri et al., 2016; Roffet-Salque et al., 2016b).

A total of 140 potsherds originating from Neolithic occupation levels covering the 6th to the 7th millennia cal BP (fifth millennium BC, Fig. 2c, Table 2 and Table 3, supplementary information) were investigated (as detailed in Kherbouche et al., 2016). Twenty-eight animal fats residues (Fig. 3a) were selected for GC-C-IRMS analyses,

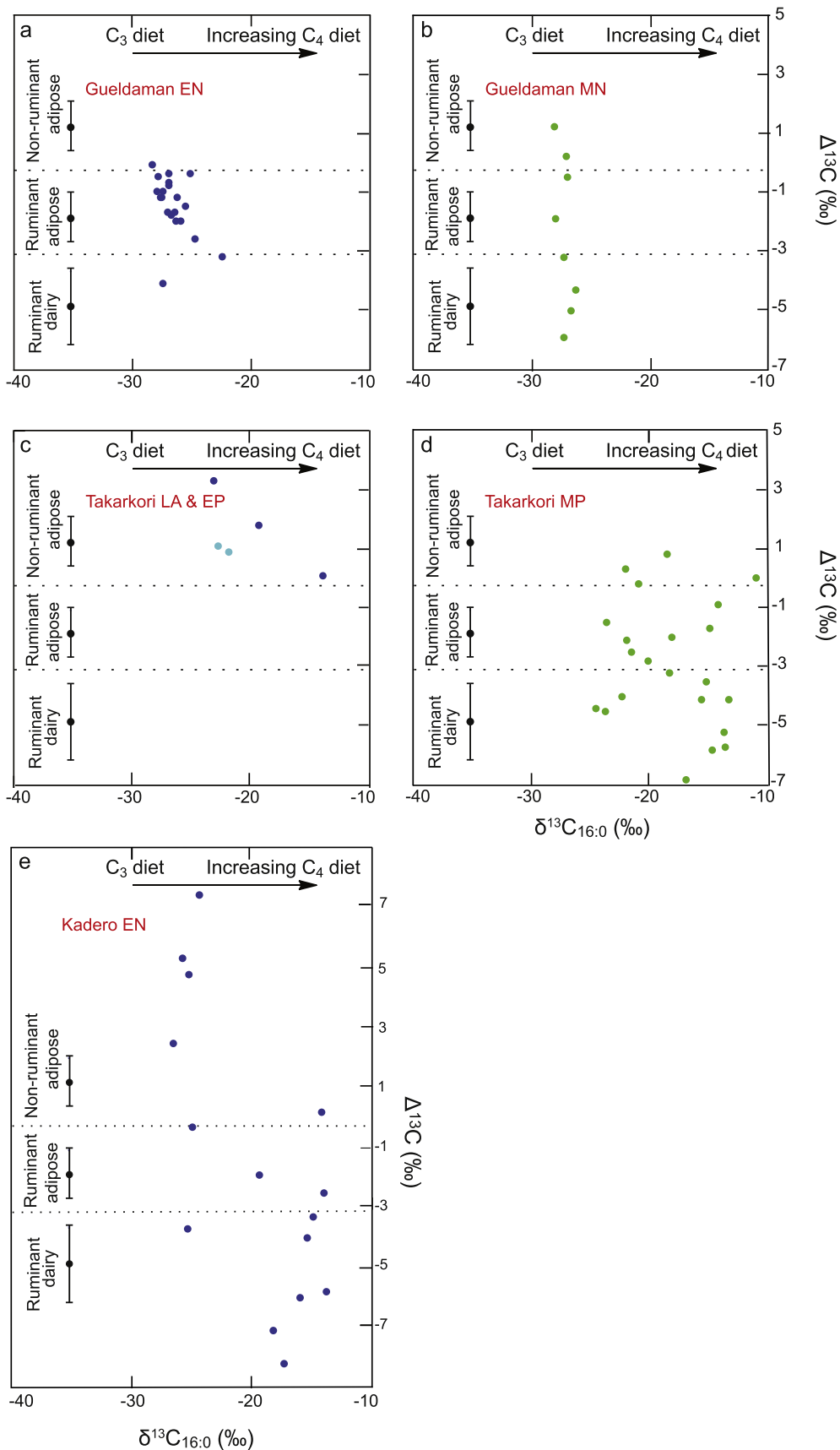
20 originating from Early Neolithic levels (UA1) and 8 from Middle Neolithic levels (UA2 and 3). Of these, the  $\Delta^{13}\text{C}$  values show that four total lipid extracts (TLEs:14%, Fig. 4a and b) can clearly be attributed to a ruminant dairy product origin, plotting within the known range of ruminant dairy products determined by analysis of modern reference dairy fats from cattle and ewes raised on a wholly C<sub>3</sub> diet in Britain and C<sub>3</sub>/C<sub>4</sub> diets in Africa (Table 2; Copley et al., 2003; Dunne et al., 2012). These data confirm the exploitation of domesticated animals and their secondary products was taking place at this Mediterranean North African Neolithic site in the fifth millennium BC (Tables 1 and 2). Of the remainder, *n* = 19 residues (68%) plot within the range for ruminant adipose products, with a further 3 residues plotting in the non-ruminant adipose product range. Two residues, GLD062 and GLD089, both with  $\Delta^{13}\text{C}$  values of  $-3.2\text{‰}$  plot close to the border between ruminant dairy and ruminant adipose values (Fig. 4a and b). Ruminant dairy products are differentiated from ruminant adipose products when they display  $\Delta^{13}\text{C}$  values of less than  $-3.1\text{‰}$  (Dunne et al., 2012; Salque, 2012). However, some overlap is observed between the observed  $\Delta^{13}\text{C}$  values of ruminant carcass and dairy fats, hence archaeological fats which plot close to the  $-3.1\text{‰}$  boundary should not be firmly interpreted as ruminant dairy or adipose products, rather it is likely that some mixing of these fats occurred in the vessels.

The  $\delta^{13}\text{C}_{16:0}$  values of the fatty acids range from  $-28.3$  to  $-22.4\text{‰}$  and the  $\delta^{13}\text{C}_{18:0}$  values range from  $-33.2$  to  $-25.5\text{‰}$  (Table 2). These values suggest that the animals producing these fats seem mainly to have subsisted on a C<sub>3</sub> plant diet, with the addition of some C<sub>4</sub> plants. This is confirmed by the mean  $\delta^{13}\text{C}_{16:0}$  and  $\delta^{13}\text{C}_{18:0}$  values which are more enriched by c. 3–4‰, respectively, in comparison to modern British reference fats. This implies that the herders and their animals were possibly living a relatively settled lifestyle, with no long distance transhumant movements, as confirmed by the archaeological evidence (Kherbouche et al., 2014).

The identification of lipid residues demonstrating animal product processing at Gueldaman Cave can be directly correlated with the archaeozoological assemblage. In the Early Neolithic, the faunal assemblage is dominated by sheep and goat (63% of NISP), with some cattle (13% of NISP) and pig (20% of NISP) being present. The Middle Neolithic sees a slight reduction in sheep and goat (45% NISP, UA2 and 42% NISP, UA3) and an increase in cattle (28% NISP, UA2 and 31% NISP, UA3) with the number of pig remains staying fairly constant (20% NISP, UA2 and 22% NISP, UA3; Kherbouche et al., 2016; Merzoug et al., 2016). In the Early Neolithic the majority of the residues originate from ruminant carcass products, perhaps reflecting processing of mainly sheep and goat, the dominant species at the site. Some possible mixing of ruminant carcass with non-ruminant carcass products may reflect either processing of pigs or hunted fauna, either contemporaneously or during the lifetime of use of the vessel (Mukherjee, 2004; Mukherjee et al., 2005). In the Middle Neolithic, processing of milk products becomes an important part of subsistence strategies at the site, originating either from the cattle or sheep/goat. However, the presence of wild fauna, such as antelope and Barbary sheep, in the faunal assemblage, suggests a continued, albeit minor, reliance on hunting. This corresponds well with the lipid residue results, as only two of the vessels sampled were used to process non-ruminant animal products (7%). As noted, these might also originate from wild boar/pig.

The age mortality profile from the Early Neolithic (level UA1) implies that the earliest domesticates were primarily exploited for their meat; with milk production increasingly becoming an important component of their subsistence practices in the Middle Neolithic (levels UA2 to UA4). This is verified by the high abundances of Class A (0–2 months) animals killed (Kherbouche et al.,





**Fig. 4.** Graphs showing the  $\Delta^{13}\text{C}$  ( $\delta^{13}\text{C}_{18:0} - \delta^{13}\text{C}_{16:0}$ ) values from potsherds from a. Gueldaman Early Neolithic (EN), b. Gueldaman Middle Neolithic (MN), c. Takarkori Late Acacus and Early Pastoral (LA, dark blue circles & EP, light blue circles), d. Takarkori Middle Pastoral (MP) and e. Kadero Early Neolithic (EN). The ranges shown here represent the mean  $\pm 1$  s.d. of the  $\Delta^{13}\text{C}$  values for a global database comprising modern reference animal fats from Africa (Dunne et al., 2012), UK (animals raised on a pure  $\text{C}_3$  diet) (Dudd and Evershed, 1998), Kazakhstan (Outram et al., 2009), Switzerland (Spangenberg et al., 2006) and the Near East (Gregg et al., 2009), published elsewhere. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2016; Merzoug et al., 2016). The cull of high numbers of Classes B-D (2–6 months, 6–12 months, 1–2 years, respectively) animals in this period (which are known to provide tender meat) suggests a mixed meat/milk economy. This correlates well with the lipid profiles as, in the Early Neolithic (UA1, Fig. 4a) where a meat economy predominates, the lipid residue results reflect the dominance of ruminant carcass product processing in the vessels. Dairy products are also processed (5%), indicating that secondary products are exploited from the earliest introduction of domesticates, albeit at a very low level. Significantly, by the Middle Neolithic (Fig. 4b), when a mixed meat/milk economy is well-established, the processing of milk becomes more commonplace, with 38% of the residues being of dairy fat origin. As previously mentioned, in two of the vessels, the  $\Delta^{13}\text{C}$  values of the fatty acids denote some mixing of carcass and milk products, and as these cannot be firmly attributed to a dairy origin, it is conceivable that dairy product processing at the site is under-represented. Interestingly, the  $\Delta^{13}\text{C}$  values show that the two incidences of wild fauna processing occur in these later levels, perhaps implying a return to some hunting practices after the early adoption (and total reliance) on domesticates as a source of meat.

### 1.7. Diet and subsistence in the Neolithic of the Libyan Sahara

In the Libyan Sahara, during the early Holocene, hunter-gatherers specialised in hunting Barbary sheep from multi activity base camps within the Acacus Mountains and small site hunting stations near lakes in the lowlands. Later, their lifestyle became more sedentary, with a broader subsistence base, largely founded on plant resources, facilitated by the introduction of grinding equipment and ceramic technology. Some animal management of Barbary sheep also appears to take place at this time (Cremaschi and di Lernia, 1999a; di Lernia, 1999, 2001; Biagetti et al., 2004, 2009; Garcea, 2006). In the Middle Holocene, the long Pastoral period denotes the adoption of cattle and sheep/goats, together with the intensive exploitation of wild cereals (Table 1). In the early period, sedentism (in the mountains) remained high with the settlement pattern in the Middle Pastoral being characterised by the seasonal exploitation of different environments, with groups practicing transhumance through summer semi-residential sites in the lowlands to winter sites in the mountains. From the end of the 6th millennium BC, the main camps were located along lake and river shores in the dune fields but over the next two millennia, increasingly arid conditions saw a move to long distance specialised nomadism with sheep and goats (Cremaschi and Di Lernia, 1999b; di Lernia, 2002; Biagetti and di Lernia, 2003).

The Takarkori rockshelter is located in the Tadrart Acacus massif, situated in the Central Sahara, in the south-western corner of Libya (Fig. 1a and b, Biagetti and di Lernia, 2013; di Lernia and Tafuri, 2013; Cremaschi et al., 2014). The site is noteworthy for the remarkable preservation of its archaeological deposit (about 1.6 m depth), over a large area, which provided evidence of more than 4000 years of human occupation, covering the Early Holocene period (Early and Late Acacus hunter-gatherers, dated between 9300 and 6100 BCE), together with Early, Middle and Late Pastoral (Neolithic) remains, dating approximately between 6400 and 2900 BCE (Table 1). This site presented a remarkable opportunity to utilise the archaeological biomarker approach to identify what foodstuffs were processed in the ceramic assemblages from each cultural horizon and thus ascertain the subsistence strategies, and their changes throughout time, practised by the prehistoric peoples living at the site (Dunne et al., 2012, 2013, 2016). Although faunal evidence is very highly fragmented and poorly preserved at Takarkori, thus precluding herd reconstructions, the  $^{14}\text{C}$  dating of sheep/goat and cattle bones unambiguously indicates the presence of early herders in this and other sites of the Acacus Mountains. as

early as 6400–5900 BCE (Biagetti and di Lernia, 2013). However, as noted, the compelling correlation between lipid residue analyses and faunal assemblages suggests that they can be used as a proxy for animal exploitation at sites where bones either do not survive or are poorly preserved (e.g. Salque et al., 2012; Cramp et al., 2014b; Smyth and Evershed, 2015; Debono Spiteri et al., 2016).

A total of 81 potsherds were sampled from the Takarkori rock shelter, of which 56 were excavated from the Middle Pastoral period (ca. 5200–3800 BCE), the remainder originating from the Late Acacus ( $n = 8$ ), and Early ( $n = 14$ ) and Late Pastoral ( $n = 3$ ) periods (Fig. 2a, Table 2 and Table 3, supplementary information). Twenty-nine residues with a typical degraded animal fats profile (Fig. 3c) were selected for GC-C-IRMS analyses; 22 originate from Middle Pastoral levels, 3 from the Late Acacus period, 2 from the Early Pastoral and the remaining 2 from the Late Pastoral period (Dunne et al., 2012, 2013). Significantly, the residues originating from the Late Acacus and Early Pastoral periods ( $n = 5$ ), where archaeological levels either do not contain faunal remains from domesticated animals (Late Acacus) or are quite rare (Early Pastoral), plot in the non-ruminant range. These likely derive from wild fauna found locally (Fig. 4c). However, the  $\Delta^{13}\text{C}$  values of the residues from the Middle Pastoral period (ca. 5200–3800 BCE, Table 2) show that 50% of these plot within, or on the edge of, the isotopic ranges for dairy fats, with a further 33% falling within the range for ruminant adipose products and the remainder corresponding to non-ruminant carcass products (Fig. 4d). The appearance of dairying products in pottery from Takarkori rockshelter correlates with the more abundant presence of cattle bones in the cave deposits from around 5200 BCE (at the beginning of the Middle Pastoral period), if not earlier, and confirms the indirect evidence of dairying provided by the remarkable rock art of the region. These data confirm that the exploitation of domesticated animals begins early in the mid-seventh millennium BC, whereas use of secondary products was taking place at this Libyan Sahara site at least from the end of the sixth millennium BC, strengthening across the 5th millennium BC (Table 1). Of the two samples originating from the Late Pastoral period, one has a dairy product and the other a ruminant adipose origin (Dunne et al., 2012).

The  $\delta^{13}\text{C}_{16:0}$  fatty acid values of the fatty acids extracted from the Takarkori potsherds range from  $-24.5$  to  $-11.0\text{‰}$  and the  $\delta^{13}\text{C}_{18:0}$  values from  $-28.9$  to  $-11.0\text{‰}$  (Table 2). This broad range ( $-13.5\text{‰}$  and  $-17.9\text{‰}$  for the  $\delta^{13}\text{C}_{16:0}$  and  $\delta^{13}\text{C}_{18:0}$ , respectively) suggests the animals producing these fats consumed an extremely wide range of plant diets either composed entirely of  $\text{C}_3$  plants, varying combinations of  $\text{C}_3$  and  $\text{C}_4$  plants to a diet comprising wholly  $\text{C}_4$  plants (Fig. 4d). This wide range of fatty  $\delta^{13}\text{C}$  values for these African potsherds is unprecedented and points to differing pastoral modes of subsistence, such as vertical transhumance, which is still practised today, by these prehistoric Saharan groups. This is confirmed by their settlement pattern based on summer sites in the lowland sand seas and winter sites (such as Takarkori) in the mountains (di Lernia, 2002), likely in response to seasonal weather patterns. The same pattern is shown by the study of funerary practices at the site (di Lernia and Tafuri, 2013) and, more generally in the area, by combining archaeological, faunal and environmental data (Biagetti and di Lernia, 2013; di Lernia et al., 2013).

## 2. Discussion and conclusion

In this study, we synthesise new and published evidence to produce a broad regional and chronological perspective of the scale and intensity of domestic animal exploitation and the inception of dairying practices in Holocene North Africa. This period of change in human subsistence is set across a large region, comprising three different pastoral trajectories; the Nile Valley, the Sahara and

Mediterranean North Africa. Each of these exist within very diverse environments and ecologies, raising questions as to whether prevailing environmental conditions dictated regional adaptations to pastoral modes of subsistence, including different animal husbandry strategies and varying levels of mobility.

Our results confirm that, in the Libyan Sahara, a full pastoral economy is already established, including dairying, by 5200 BCE. This is at least one thousand years after domesticates first appear in the region (Biagetti and di Lernia, 2013; di Lernia and Tafuri, 2013) thus it is conceivable that dairying began before this date but a lack of samples currently precludes the testing of this hypothesis. It should also be considered that the main use of the Takarkori site during the Early Pastoral was of a funerary nature, with most of the residential area strongly eroded and poorly preserved (di Lernia and Tafuri, 2013). Following this, evidence for low-level dairying is first seen at Gueldaman Cave, at c. 5000–4900 BCE with a full pastoral economy appearing well-established by 4400–3900 BCE, approximately one thousand years later than at Takarkori, Libyan Sahara. Finally, our results demonstrate that a full dairying economy was also being practised at Kadero, Sudan, by at least 4600 BCE and possibly at 5000 BCE. Unfortunately, no data are available to determine when dairying may have begun at the site.

Thus, questions regarding the scale and intensity of dairy product exploitation from its inception in these different regions in North Africa can only be partly addressed. At Gueldaman Cave, in Mediterranean north Africa, the age mortality profile from the earliest level suggests in fact that the first domesticates were mainly exploited for their meat; with milk production increasingly becoming an important component of their subsistence practices in later levels (Kherbouche et al., 2016; Merzoug et al., 2016). This compares well with the lipid profiles as, in the earliest level where a meat economy predominates, the lipid residue analyses reflect a much higher incidence of carcass product processing in the vessels, although milk and its products are also processed (5%), suggesting that low-level secondary product exploitation ensues from the earliest introduction of domesticates. Significantly, in later levels, where a mixed meat/milk economy is well established, the processing of milk becomes more commonplace, with 50% of the residues being of dairy product origin. At Takarkori rockshelter the faunal remains were very highly fragmented and poorly preserved thus precluding herd reconstructions. As noted, little information can be gleaned on dairy processing in the Early Pastoral levels as only a small number of sherds were available for analysis ( $n = 4$ ), of these 2 yielding sufficient lipids for analysis plotted in the non-ruminant fat range, probably deriving from wild fauna found locally (Dunne et al., 2012). Furthermore, only the burial area was fairly well-preserved, with the rest of the site strongly denuded by wind erosion. However, in the Middle Pastoral period, once domesticates are well-established in the region, and the site much better preserved, the incidence of dairy product processing in the vessels is directly comparable to organic residues from Gueldaman Cave, comprising 38% of the assemblage. Lastly, the potsherds analysed from Kadero derive solely from one period, the Early Neolithic, and therefore the timing of the inception of dairying practices cannot be ascertained. However, in terms of the scale of dairy product exploitation, a total of 47% of samples comprise dairy residues. This suggests a developed pastoral economy, but finer chronological resolution of the pottery residues from the site together with analysis of potsherds from other Nile Valley sites with longer chronological spans might help to further resolve this.

These data suggest that, despite, different temporal trajectories, the earliest pastoral economies were mainly directed to meat exploitation, with scarce evidence of milk processing. Once dairying becomes an established practice in all three regions, it seems to play a significant role in local diet and subsistence

practices, with around c. 40–50% of all vessels analysed from each site being used to process dairy products. Although no meaningful conclusion can be drawn across all three sites (due to the absence of data), in terms of the scale of dairy product exploitation from its inception, the findings from Gueldaman suggest that early dairying (at 5% of residues) was of minor importance in comparison to carcass product processing. This seems to imply that the first African pastoralists were aware of milk as a dietary resource but were only able to practice milking their animals on a small scale, perhaps because of the technological difficulties involved. Clearly, they persevered, likely for the benefits milking provided (Vigne and Helmer, 2007). Our results also show that the development of herding practices was essentially a site-specific phenomenon, mirroring autonomous trajectories of pastoral specialization through time.

Furthermore, the lipid residue results confirm that the processing and consumption of ruminant carcass products in pottery across all three sites were clearly an important element of local dietary strategies. The type of ruminant exploited varies between regions, with the archaeozoological assemblages from the Sahara (Corridi, 1999; Gautier, 2002; Hassan, 2002) and Nile Valley (Gautier and Van Neer, 2011) indicating the earliest domesticates were cattle although at Takarkori they are virtually contemporaneous with sheep/goat (di Lernia, 2013). However, in the Mediterranean Neolithic, sheep and goat appear first (Merzoug et al., 2016).

The remarkably wide range of  $\delta^{13}\text{C}$  values from the lipid residues at these three sites offers significant potential not only to determine subsistence strategies but also investigate animal husbandry practices. Organic residue analysis can be a powerful proxy both for the mobility of past populations and in discerning the past 'isoscapes' they inhabited (West et al., 2010; Dunne et al., 2012), especially if combined with isotopic study of human and animal remains (di Lernia and Tafuri, 2013; di Lernia et al., 2013). The foods that animals eat exhibit characteristic isotopic signatures (Gannes et al., 1997) and isotopic analyses ( $\delta^{13}\text{C}$ ) of fatty acids extracted from archaeological potsherds are therefore a reflection of the consumed diet, providing information about the environment in which the animals foraged (Copley et al., 2003; Mukherjee et al., 2005). At Gueldaman Cave, the relatively narrow range of  $\delta^{13}\text{C}_{16:0}$  values ( $-28.3$  to  $-22.4\text{‰}$ ) suggests that the animals producing these fats were subsisting on a diet comprising mainly  $\text{C}_3$  plants, with minor  $\text{C}_4$  input. This implies that the herders and their animals were possibly living a relatively settled lifestyle, with no long distance transhumant movement, as confirmed by the archaeological evidence (Kherbouche et al., 2014). This is in contrast to the Saharan Neolithic, where climatic and environmental conditions are known to have been more unpredictable (e.g. deMenocal et al., 2000), as demonstrated by the unprecedented range and distribution of the  $\delta^{13}\text{C}_{16:0}$  fatty acid values from Takarkori ( $-24.5$  to  $-11.0\text{‰}$ ). The animals giving rise to these fats subsisted on an extensive range of different forages either composed entirely of  $\text{C}_3$  plants, or various combinations of  $\text{C}_3$  and  $\text{C}_4$  plants, or wholly of  $\text{C}_4$  plants, possibly suggesting a transhumant lifestyle. This is corroborated by recent isotope studies on human and faunal remains from Takarkori rock shelter (di Lernia and Tafuri, 2013) as well on cattle remains from Middle Pastoral ceremonial sites in the Messak plateau and surroundings (di Lernia et al., 2013). The Kadero residues also demonstrate a broad range of  $\delta^{13}\text{C}_{16:0}$  values,  $-26.5$  to  $-13.7\text{‰}$ ; however, their interpretation is complex. The dairy residues appear to originate from animals subsisting on a  $\text{C}_4$  diet, perhaps suggesting some specialised management of these animals, possibly foddering them on the wild grasses of the savannahs. This is in contrast to animal products, likely hunted animals, processed in other vessels, which appear to be consuming a much more  $\text{C}_3$  diet. This may be because these wild fauna were grazing

close to the Nile, where the vegetation is likely to be less water-stressed and possibly of a C<sub>3</sub> origin.

In conclusion, complementary studies of lipid residues with age-at-death and mortality profiles reconstructed from faunal assemblages where possible, provide compelling evidence, for the first time, of the timing and extent of dairy product exploitation across the three different pastoral lifeways found in Mediterranean North Africa, the Nile Valley and the Sahara. The development of a pastoral economy in each region, including dairying as an important component of subsistence strategies, was clearly a multi-scalar, multi-faceted phenomenon. Firstly, there is an interval between the introduction of domesticates to a region and the beginnings of dairying, likely explained by the degree of replacement of domestic stock in areas densely inhabited by foragers and the timing and degree of acceptance and implementation of new technologies of dairying and animal management strategies (di Lernia, 2013). The introduction of domestic animals was a long, intermittent, multi-linear process that produced different outcomes according to specific local traditions, climate and environmental contexts and type of pastoral strategy. Dairying first appears in the Libyan Sahara, with a fully developed pastoral economy, based on vertical transhumance, being present at 5200 BCE, if not earlier. This is supported by their settlement pattern based on summer sites in the lowland sand seas and winter sites (such as Takarkori) in the mountains (di Lernia, 2002). Our data suggest the first dairying in Mediterranean north Africa occurs at 5000/4900 BCE, albeit at low levels, with a full pastoral economy being in place by 4400–3900 BCE. Finally, dairying appears at least as early as c. 4600 BCE in the Nile Valley.

Finally, the different animal husbandry strategies, suggested by the stable carbon isotope values from the animal products being processed in the pottery, demonstrate how prevailing environmental conditions likely dictated regional adaptations to pastoral modes of subsistence, i.e. different grazing strategies and varying levels of mobility.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.quaint.2017.06.062>.

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