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## CLASSIFICATION

Major: Social sciences. Minor: Anthropology

## FULL TITLE

**Molecular and isotopic evidence for milk, meat and plants in prehistoric eastern African herder food systems reveal changing selective contexts for lactase persistence**

## ABBREVIATED TITLE

**Ceramic residues reveal early milk, meat, and plant processing by ancient E. African herders**

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## ABSTRACT

The development of pastoralism transformed human diets and societies in grasslands worldwide. The long-term success of cattle herding in Africa has been sustained by dynamic food systems, consumption of a broad range of primary and secondary livestock products, and the evolution of lactase persistence, which allows digestion of lactose into adulthood and enables the milk-based, high protein, low-calorie diets characteristic of contemporary pastoralists. Despite the presence of multiple alleles associated with lactase persistence in ancient and present-day eastern African populations, the contexts for selection for LP and the long-term development of pastoralist foodways in this region remain unclear. Pastoral Neolithic (c. 5,000–1,200 BP) faunas indicate that herders relied on cattle, sheep, and goats, and some hunting, but direct information on milk consumption, plant use, and broader culinary patterns is rare. Combined chemical and isotopic analysis of ceramic sherds ( $n=125$ ) from Pastoral Neolithic archaeological contexts in Kenya and Tanzania, using compound-specific  $\delta^{13}\text{C}$  and  $\Delta^{13}\text{C}$  values of the major fatty acids (FAs), provides the earliest chemical evidence for milk, meat, and plant processing by ancient herding societies in eastern Africa. These data provide the first direct evidence for milk product consumption and reveal a history of reliance on animal products and other nutrients, likely extracted through soups or stews, and plant foods. They document a 5,000-year temporal framework for East African pastoralist cuisines, evidence of milk prepared or served in ceramic vessels, and changing cultural contexts through time for selection for the distinctive eastern African genetic basis for lactase persistence.

## SIGNIFICANCE STATEMENT

Lipid residue analysis of archaeological ceramics provides the earliest, and first, direct chemical evidence for milk, meat, and plant consumption by pastoralist societies in eastern Africa. Data for milk-inclusive food systems (c. 5,000–1,200 BP) reveal changing selective pressures for lactase persistence and provide support for models of gene-culture co-evolution among pastoral populations.

## MAIN TEXT

### Introduction

Pastoralism is a dominant form of food production in grassland ecosystems globally (1), and genetic histories of pastoralist populations reflect complex interplays between human migrations, interactions, and culinary practices (2). In eastern Africa, mobile herding communities in marginal dryland environments have historically relied on milk-based, high-protein, low-calorie diets (3), facilitated by multiple genetic bases for lactase persistence (LP) and digestion of milk into adulthood. Although the earliest evidence for cattle, sheep, and goats dates to the Pastoral Neolithic (PN; c. 5,000–1,200 years before present, BP), when herders spread into eastern Africa, little is known about reliance on milk as a food, settings for selection for East African genetic bases for lactase persistence, or the long-term development of highly

specialized pastoralist foodways. Direct evidence for the consumption of milk, for example, is absent in PN and later archaeological records.

Genetic bases for LP facilitate the ability to survive on livestock milk, as regulatory mutations that affect production of the enzyme lactase and its post-weaning retention enable digestion of milk sugars (lactose). It has long been hypothesized that LP is selected for in pastoral populations through gene-culture co-evolution but roles of cuisine, gut microbiomes, and population interactions are poorly understood given highly variable selection contexts worldwide (e.g., 4). In southwestern Asia, archaeological data on dairy-based pastoralism that emerged after ~11,000 BP suggest relatively sedentary, agropastoral contexts with foci on sheep/goat husbandry (5). African herding systems, beginning ~8,000 BP in what is now the Sahara, were characterized by greater mobility, later limited cultivation, and dietary foci on cattle. In eastern Africa today, milk and milk products from cattle (or camels in more arid regions), sheep, and goat provide as much as 60-90% of total calories (6–8). Milk shortages during droughts or dry seasons increase vulnerabilities to malnutrition (9–11), and result in increased consumption of meat and within-bone nutrients. Milk and meat are also complemented by seasonally-available wild plant foods and, today, introduced staples (e.g. maize and beans). Tishkoff and colleagues (12, 13) suggest that strong selection resulted in the appearance of the C-14010 genetic variant for the LP trait in eastern African populations an estimated ~6,800-2,700 years ago. Evidence for early milk consumption is lacking, but discovery of an individual buried in northern Tanzania, dating to 2,200- 2,150 BP, with the C-14010 allele provides a pastoral context for selection (14). The existence of multiple other genetic variants associated with the LP phenotypic trait in contemporary eastern African populations (12, 13) distinguishes this region from most of Eurasia where a single genetic basis for LP is common (2). All LP variants are present at relatively low frequencies (<45%) (13) in eastern Africa and it is likely this was also the case in the past (14). In the absence of LP, herder dependence on milk can be facilitated by preparation of fresh milk into more easily digested fermented milk products (2, 13).

Although it is clear from the human genetic data that the ability for herders to digest milk must have been strongly adaptive in eastern Africa, lack of direct information on when and where milk was drunk, how ancient herders prepared their food, and how herders buffered milk shortages has constrained understanding of prehistoric selective contexts for LP. Integrated archaeological and molecular evidence can provide a deeper understanding of when, where, and why LP emerged in eastern Africa, in addition to shedding light on broader dietary patterns. Here, we report lipid residue analyses of 125 ceramic vessels from PN archaeological contexts in Kenya and Tanzania. These data provide the first direct evidence for meat, milk, and plant processing or storage by ancient eastern African herders, and offer a globally relevant perspective on the origins of pastoralist dietary adaptations and the evolution of milk-centered husbandry systems.

### **Pastoral Neolithic herders**

During the PN, communities herding cattle, sheep, goat, and donkey spread throughout the eastern African Rift Valley and beyond, interacting with indigenous hunter-gatherers. Livestock first appear in the Turkana Basin of northwestern Kenya during a period of aridity and social change c. 5,000-4,500 cal BP (3) when herder-fishers built a series of megalithic “pillar

sites.” Some of these are communal cemeteries where people deposited highly decorated ceramic vessels (15, 16). After c. 3300 cal BP there was a florescence of specialized herding economies throughout south-central Kenya and into Tanzania. Herders moved into wetter, topographically diverse, and more productive pastoral grazing lands, where cattle herds can produce milk almost year-round (17–19).

The sites and samples chosen for this study are broadly representative of the archaeological diversity of the PN. They include ceremonial and habitation sites, span the Turkana Basin in Kenya to the north-central Tanzanian highlands (Figure 1), and cover the three major PN material culture traditions (see Table 1 for references). **Jarigole** (Gbjj1, c. 5,000–4,500 cal BP) is a megalithic pillar site on the east side of Lake Turkana, and **Dongodien** (Gaj4, c. 5,000–4,500 cal BP) is a roughly contemporaneous open-air habitation site on the east side of Lake Turkana. **Ngamuriak** (GuJf6, c. 2,000 cal BP) is a settlement site in the Loita-Mara region of southwestern Kenya. **Luxmanda** (c. 3,000 cal BP) is another large open-air settlement site, located on the Mbulu Plateau in north-central Tanzania. A description of sampling strategies and a list of lipid-yielding samples with contextual information can be found in SI Appendix, Table SI1; sherd photographs are in Figure 2. Previously published radiocarbon dates for each site, along with newly generated compound-specific radiocarbon dates on extracted lipids (20), are in SI Appendix, Table SI2.

## Lipid residue results

### *Recovery rates and concentrations*

Lipid analysis and interpretations for PN ceramics were performed using established protocols (e.g., 21, 22). A total of 125 ceramic sherds were sampled from Jarigole ( $n=20$ ), Dongodien ( $n=20$ ), Ngamuriak ( $n=22$ ), and Luxmanda ( $n=63$ ). Lipid recovery rates varied, with rates at the two earlier sites, Jarigole and Dongodien, being lower (25%,  $n=5$  at each site) than at Luxmanda (38%,  $n=24$ ) and especially at Ngamuriak where lipid recovery was very high (82%  $n=18$ ). Lower lipid recovery rates may be taphonomic but more likely suggest different patterns of vessel use. The mean lipid concentrations of the Jarigole and Dongodien sherds are 0.7 and 0.08 mg g<sup>-1</sup>, respectively (Table 1), with maximum lipid concentrations of 1.9 mg g<sup>-1</sup> (GAJ003) and 0.2 mg g<sup>-1</sup> (GBJ014) whereas the mean lipid concentrations for Luxmanda (1.3 mg g<sup>-1</sup>) and Ngamuriak (3.6 mg g<sup>-1</sup>) and the maximum lipid concentrations at these sites are considerably higher, Luxmanda (11.5 mg g<sup>-1</sup>, LUX019) and Ngamuriak (29.4 mg g<sup>-1</sup>, NMK018). Several sherds from both later sites contain high concentrations of lipids: e.g., LUX003, 4.6 mg g<sup>-1</sup>, LUX019, 11.5 mg g<sup>-1</sup>, LUX038, 5.9 mg g<sup>-1</sup>, LUX043, 2.7 mg g<sup>-1</sup>, LUX052, 2.0 mg g<sup>-1</sup>, NMK004, 2.3 mg g<sup>-1</sup>, NMK005, 6.2 mg g<sup>-1</sup>, NMK006, 13.2 mg g<sup>-1</sup>, NMK8,9,10, 3.4 mg g<sup>-1</sup> and NMK018, 29.4 mg g<sup>-1</sup>). These vessels were likely subjected to sustained use in the processing of high fat-yielding resources.

### *Meat and milk*

Analysis of the total lipid extracts (TLEs,  $n=125$ ) from all sites, using gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS), demonstrated that 52 sherds contained sufficient concentrations (>5μg g<sup>-1</sup>) of lipids to allow reliable interpretation (23). These extracts comprised lipid profiles which demonstrated that palmitic (C<sub>16</sub>) and stearic (C<sub>18</sub>)

fatty acids, typical of a degraded animal fat (Figure 3a and b), were the most abundant components (e.g., 24). Further analyses by gas chromatography-combustion-isotope-ratio mass spectrometry (GC-C-IRMS) characterized the source of these animal products through determination of the  $\delta^{13}\text{C}$  values of the major fatty acids,  $\text{C}_{16:0}$  and  $\text{C}_{18:0}$  (Figure 4), which allows differentiation between carcass products from ruminant and non-ruminant animals and between ruminant dairy and carcass products (21, 24).

At Jarigole ( $n=5$ ), one lipid residue sample plots within the non-ruminant (or, possibly, plant) range, with the remaining four plotting within the ruminant adipose region, although these are located at the extent of the ranges, suggesting they may include mixtures of dairy and non-ruminant products, respectively. Ruminant dairy fats are differentiated from adipose fats when they display  $\Delta^{13}\text{C}$  ( $\delta^{13}\text{C}_{18:0} - \delta^{13}\text{C}_{16:0}$ ) values of less than  $-3.1\text{‰}$  (25). At Dongodien ( $n=5$ ), one vessel plots in the ruminant dairy range, with two vessels plotting in the ruminant adipose range and a further two plotting in the non-ruminant/plant range. Non-ruminant mammals potentially present in the area during the PN include equids (zebra and donkey), suids (warthog and bushpig), and small mammals such as hare and hyrax. At Jarigole and Dongodien,  $\delta^{13}\text{C}_{16:0}$  values (range  $-26.3$  to  $-16.8\text{‰}$ ) suggest that animals were subsisting on both  $\text{C}_3$  and  $\text{C}_4$  plants as confirmed by other datasets at these sites (17, SI Appendix, Figure SI2).

The majority of the lipid-bearing residues at the two later PN sites, Luxmanda (83%,  $n=20$ ) and Ngamuriak (94%,  $n=17$ ), plot within the ruminant carcass range, confirming the dominant use of ceramic vessels for meat processing.  $\delta^{13}\text{C}_{16:0}$  values (range  $-22.1$  to  $-12.0\text{‰}$ ) for these sites suggest that animals were subsisting mainly on  $\text{C}_4$  plants, which aligns with stable carbon isotope data for livestock tooth enamel across southern Kenya and northern Tanzania (17, 26, 27, SI Appendix, Figure SI2). One vessel at Luxmanda, LUX004, with a  $\Delta^{13}\text{C}$  of  $-5.4\text{‰}$ , plots firmly in the ruminant dairy region, with a further vessel (LUX025  $-3.1\text{‰}$ ), plotting at the extent of the range. Similarly, at Ngamuriak, vessel NMK020 plots close to the top of the range ( $\Delta^{13}\text{C}$  of  $-3.4\text{‰}$ ), with vessel NMK8,9,10 plotting very close to the border at  $-3.0\text{‰}$ , suggesting mixing of meat and milk products. These results confirm, at both sites, at least limited exploitation of milk or milk products, such as yogurt, ghee, or cheese.

### *Plant processing*

At Luxmanda, two vessels, LUX032 and LUX057, plot within the non-ruminant/plant region with enriched  $\Delta^{13}\text{C}$  values of  $2.9$  and  $3.7\text{‰}$ , respectively. Interestingly, both vessels have low lipid concentrations, often indicative of plant processing, and the lipid profile of LUX032 includes a series of odd-over-even  $n$ -alkanes, dominated by  $\text{C}_{31}$ , likely originating from  $\text{C}_3$  or  $\text{C}_4$  wild grasses or lake-margin plants, such as sedges (28–31). A further vessel, LUX030, is dominated by high concentrations of even-over-odd numbered long-chain fatty acids, maximizing at  $\text{C}_{26}$ , again strongly indicative either of an origin in leaf or stem epicuticular waxes (20).

### *Freshwater resources*

Fatty acid methyl esters (FAMES) from all lipid residues were analyzed by GC-MS in SIM mode to check for the presence of aquatic biomarkers, namely  $\omega$ -( $o$ -alkylphenyl) alkanolic acids (APAAs), vicinal dihydroxy fatty acids (DHYAs) and isoprenoid fatty acids (IFAs). These are routinely used to detect both marine and freshwater product processing (32–34), however, no

freshwater biomarkers were detected here. Despite the prevalence of fish bones at Dongodien (35), freshwater resources, such as fish, may not have been prepared by boiling in pots and could have been cooked in other ways such as roasting, salting, or smoking.

## Discussion

Lipid residue analysis of archaeological ceramics provides the earliest, and first, direct chemical evidence for milk, meat, and plant consumption by pastoralist societies in eastern Africa. Our results demonstrate that the earliest herders in the region, at Dongodien, *c.* five thousand years ago, drank milk and/or ate milk-based products. These data provide an extended chronology for selection for the distinctive eastern African basis for lactase persistence (C-14010), and raise questions about whether these herders may have carried an allele for LP (e.g. G-13907) common in Sudan or Ethiopia today (see 12, 13). Dietary mediation may have been significant for digestion of milk as well. Meat, fat, and/or bones from livestock and wild fauna (non-ruminants) were also cooked or served in ceramic pots found at the Dongodien settlement and the Jarigole mortuary site. These food residues are consistent with faunal data from Dongodien; however, it is notable that few remains of non-ruminant mammals (hyrax and hare) were identified in the faunal assemblage (35). The organic residue data reveal that at least some highly-decorated Nderit ceramics found at both early PN mortuary contexts and habitation sites were used in the storage, preparation, or serving of food. All five vessels with preserved lipids at Jarigole, and three from Dongodien, display low lipid concentrations, suggesting they were only used sporadically for cooking or for serving foodstuffs. At Dongodien, two additional vessels (GAJ003 and GAJ013) yielded high lipid concentrations, indicating their possible use as cooking pots, although no use-wear such as sooting on any Nderit pottery indicates use over fire.

In the wetter southern highlands and richer grasslands, faunal remains show that later herders with different mortuary and ceramic traditions *c.* 3,000 BP—2,000 BP kept large cattle herds and depended on livestock, with little to no reliance on wild fauna (36, 37). Lipid residues demonstrate that herders at the Luxmanda and Ngamuriak settlement sites consumed milk or milk-based products processed in pots, likely aiding the digestion of lactose. Sherds preserving milk residues were present at low frequencies, but comparison with lipid residues extracted from ceramics used by heavily milk-reliant Samburu pastoralists in northern Kenya today demonstrates a broadly similar pattern (38). In Samburu, this pattern reflects container choices rather than degree of reliance on milk in the diet (9). Meat and bones are cooked in pots while milk—for ceremonial and daily use—is generally collected, stored, and processed in wooden vessels and gourds, which rarely preserve at archaeological sites.

Lipid assemblages at Ngamuriak and Luxmanda are dominated by ruminant carcass product processing, which corresponds well with highly fragmented cattle, sheep, and goat bone assemblages (18, 26). Extremely high lipid concentrations from nearly all Ngamuriak vessels and many of the Luxmanda vessels indicate that ceramic technologies throughout the PN played a critical role in the repeated preparation of meat, bones, marrow and/or fat, likely through breakage and boiling of bones. Furthermore, lipid profiles at Luxmanda provide the first evidence for plant processing in the PN. Given otherwise good preservation of lipids at Luxmanda, the large number of sherds with no detectable lipid residues may come from pots that served other functions such as serving or storage of low lipid-yielding foods.

At a larger scale, our findings demonstrate the importance of milk products, carcass processing and plant consumption to food-producing economies as herders spread throughout eastern Africa following Saharan expansion. Lipid residue data are relatively consistent across a wide geographic area, different site types, and different material traditions: Throughout the entire PN herders used pots, albeit infrequently, to either process or serve milk or milk-based products. This time frame provides a relatively long period in which selection for the lactase persistence trait may have occurred within multiple groups in eastern Africa, which supports genetic estimations. Settings for selection differed with social and economic organization and environment. Diversified reliance on livestock, fishing, and hunting at Lake Turkana 5,000 years ago provided herders in this arid region with alternatives to reliance on milk or slaughtering of livestock during times of seasonal shortage or drought. Conversely, lipid residue and faunal data reveal that pastoralists who lived at Ngamuriak and Luxmanda in the rich grazing lands of southwestern Kenya and northern Tanzania relied almost exclusively on their livestock, and possibly plants. Given pastoralist specialization, selection for LP in east Africa (the C-14010 allele) may have been stronger among specialized pastoral groups after 3,100 BP in more southerly regions than earlier at Lake Turkana in the north.

The earliest herders in northern Kenya 5,000 years ago drank milk or ate milk-based products, and also used at least some ceramic vessels found at both ceremonial and settlement sites for processing or serving carcass fats from livestock. Later specialized herders in southwest Kenya and north-central Tanzania c. 3,000 – 2,000 BP intensively processed livestock carcass fats in ceramic vessels, similar to how Samburu herders use ceramics today. These results reveal the changing significance of livestock, and their milk, to herder diets and have broader relevance for understanding the biological histories of herders in eastern Africa. These histories are likely the result of gene-culture co-evolution involving complex interplays among migrations, diverse livestock management strategies, local ecologies, and dietary and culinary adaptations spanning thousands of years.

## **MATERIALS AND METHODS**

Lipid analysis and interpretations were performed using established protocols described in detail in earlier publications (e.g., 21, 22). All solvents used were HPLC grade (Rathburn) and the reagents were analytical grade (typically > 98% of purity). Briefly, ~2 g of potsherd were sampled and surfaces cleaned with a modelling drill to remove any exogenous lipids. The sherds were ground to a powder and an internal standard, typically 40 µg, was added to enable quantification of the lipid extract (*n*-tetratriacontane; Sigma Aldrich Company Ltd). Following the addition of 5 mL of H<sub>2</sub>SO<sub>4</sub>/MeOH 2 - 4% ( $\delta^{13}\text{C}$  measured), the culture tubes were placed on a heating block for 1 h at 70 °C, mixing every 10 min. Once cooled, the methanolic acid was transferred to test tubes and centrifuged at 2500 rpm for 10 min. The supernatant was then decanted into another furnace culture tube (II) and 2 mL of DCM extracted double distilled water was added. In order to recover any lipids not fully solubilized by the methanol solution, 2 x 3 mL of hexane was added to the extracted potsherds contained in the original culture tubes, mixed well and transferred to culture tube II. The extraction was transferred to a clean, furnace 3.5 mL vial and blown down to dryness. Following this, 2 x 2 mL hexane was added



directly to the H<sub>2</sub>SO<sub>4</sub>/ MeOH solution in culture tube II and whirlmixed to extract the remaining residues. This was transferred to the 3.5 mL vials and blown down until a full vial of hexane remained. Aliquots of the fatty acid methyl esters (FAMES) were derivatized using *N,O*-bis(trimethylsilyl)trifluoroacetamide (BSTFA) containing 1 % trimethylchlorosilane (TMCS; Sigma Aldrich Company Ltd.; 20 µL; 70°C, 1 h). Excess BSTFA was removed under nitrogen and the derivatized FAME was dissolved in hexane prior to GC, GC-MS and GC-C-IRMS.

All FAMES initially underwent high-temperature gas chromatography using a gas chromatograph (GC) fitted with a high temperature non-polar column (DB1-HT; 100% dimethylpolysiloxane, 15 m x 0.32 mm i.d., 0.1 µm film thickness). The carrier gas was helium and the temperature program comprised a 50°C isothermal hold followed by an increase to 350°C at a rate of 10°C min<sup>-1</sup> followed by a 10 min isothermal hold. A procedural blank (no sample) was prepared and analyzed alongside every batch of samples. Further compound identification was accomplished using gas chromatography-mass spectrometry (GC-MS). FAMES were then introduced by autosampler onto a GC-MS fitted with a non-polar column (HP-1; 100% dimethyl polysiloxane stationary phase; 60 m x 0.25 mm i.d., 0.1 µm film thickness). The instrument was a ThermoFinnigan single quadrupole TraceMS run in EI mode (electron energy 70 eV, scan time of 0.6 s). Samples were run in full scan mode (*m/z* 50–650) and the temperature program comprised an isothermal hold at 50°C for 2 min, ramping to 300°C at 10° min<sup>-1</sup>, followed by an isothermal hold at 300°C (15 min). Data acquisition and processing were carried out using HP Chemstation software (Rev. B.03.02 (341), Agilent Technologies) and Xcalibur software (version 3.0). Peaks were identified on the basis of their mass spectra and gas chromatography (GC) retention times, by comparison with the NIST mass spectral library (version 2.0).

Carbon isotope analyses by GC-C-IRMS were also carried out using a GC Agilent Technologies 7890A coupled to an Isoprime 100 (EI, 70eV, three Faraday cup collectors *m/z* 44, 45 and 46) via an IsoprimeGC5 combustion interface with a CuO and silver wool reactor maintained at 850°C. Instrument accuracy was determined using an external FAME standard mixture (C<sub>11</sub>, C<sub>13</sub>, C<sub>16</sub>, C<sub>21</sub> and C<sub>23</sub>) of known isotopic composition. Samples were run in duplicate and an average taken. The δ<sup>13</sup>C values are the ratios <sup>13</sup>C/<sup>12</sup>C and expressed relative to the Vienna Pee Dee Belemnite (VPDB), calibrated against a CO<sub>2</sub> reference gas of known isotopic composition. Instrument error was ±0.3‰. Data processing was carried out using Ion Vantage software (version 1.6.1.0, Elementar). These methods have previously been detailed in, for example, (48). Data Availability Statement: All data discussed in the paper will be made available to readers.

## AUTHOR CONTRIBUTIONS

The project was designed by JD, KR, K-M, KG and RPE and the paper was written by KG, JD, FM, MP, AJ, PR, and RPE. JD, TG, CWD and HLW performed analytical work and data analysis. EC performed radiometric analyses. JK conducted a pilot study. Fieldwork at Luxmanda was co-directed by AG, AM, MP, and KG, while PR and FM directed excavations at Ngamuriak. All living authors read and approved the final manuscript.

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## FIGURE LEGENDS

Figure 1. Density and distribution of excavated Pastoral Neolithic sites in eastern Africa: major sites with known coordinates are marked with black dots. Sites sampled for this study are marked with red triangles. Base map source: Natural Earth.

Figure 2. Examples of sherds from each site containing lipid residues. Sherds *a-g* are considered “Nderit” pottery (see 44) from the Turkana Basin; exterior surface is shown on the left, interior surface is shown on the right. Jarigole (*a: GBJ001, b: GBJ014, c: GBJ016, d: GBJ018, e: GBJ007*): *a-d* are “Classic Nderit” basketry-like vessels with unidentified forms; for *a* and *b* note internal scoring, for *c* note internal shallow impressions. Sherd *e* has incised grooves in a geometric pattern, common for shallow bowls. Dongodien (*f: GAJ003, g: GAJ012*): *f* is “Classic Nderit,” *g* has wide grooves, three undecorated sherds with lipid residues not pictured. Luxmanda (*h: LUX019, i: LUX025, j: LUX065, k: LUX059*): sherds are “Narosura” pottery, common to Savanna Pastoral Neolithic (SPN) sites. Forms are open-mouthed bowls or globular vessels with comb-stamping or incising in bands under rims. Ngamuriak (*l: NMK006, m: NMK8/9/10*): sherds are “Elmenteitan” pottery, undecorated with forms including straight-sided or globular bowls/pots.

Figure 3. Partial gas chromatograms of trimethylsilylated FAMES from pottery extracts a) lipid distributions in LUX032 are indicative of leafy wax processing and b), c) and d) showing typical degraded animal fat chromatograms, dominated by C<sub>16</sub> and C<sub>18</sub> fatty acids, from Dongodien, Luxmanda and Ngamuriak, respectively, Circles, *n*-alkanoic acids (fatty acids, FA); triangles, *n*-alkanes; IS, internal standard, C<sub>34</sub> *n*-tetratriacontane.

Figure 4. Graphs (a-d) showing the  $\Delta^{13}\text{C}$  ( $\delta^{13}\text{C}_{18:0} - \delta^{13}\text{C}_{16:0}$ ) values from the potsherds at each of the sampled sites: Jarigole, Dongodien, Luxmanda and Ngamuriak. The ranges shown here represent the mean  $\pm$  1 s.d. of the  $\Delta^{13}\text{C}$  values for a global database comprising published modern reference animal fats from Africa (25), UK (animals raised on a pure C<sub>3</sub> diet) (21), Kazakhstan (45), Switzerland (46), and the Near East (47).

Table 1. Summary table of archaeological information for sampled sites.

Site	Date range	Archaeological Tradition	Site description	Ceramics	Other material culture	Fauna	References
Jarigole (Gbj1)	c. 5,000-4,500 cal BP	Nderit	Megalithic communal cemetery on the eastern side of Lake Turkana.	“Nderit” ceramics; vessels include a variety of finely-made forms and decorative styles such “Classic Nderit” basket-like bowls, often with internal scoring. Other vessels have red “burnished ripple” designs or incised geometric patterns.	Diverse personal ornamentation including stone, bone, and ostrich eggshell beads, a relatively small lithic assemblage (predominantly obsidian), and zoomorphic ceramic figurines of wild fauna and probable domestic cattle.	Only fauna reported are fish vertebrae and small fragments of bovid tooth enamel.	(39)
Dongodien (Gal4)	c. 5,000-4,500 cal BP	Nderit	Open-air settlement site on the eastern side of Lake Turkana.	“Nderit” pastes and decorative techniques appear similar to those seen at Jarigole and Lothagam North.	Microlithic, predominantly obsidian assemblage, one unidentified incised bovid bone.	Generalized pastoralism with small stock, cattle, and wild fauna including fish.	(35, 40)
Ngamuriak (GuJf6)	c. 2,000 cal BP	Elmenteitan	Open-air settlement site in the Loita-Mara region of southwestern Kenya.	“Elmenteitan” ceramics; vessels are typically undecorated but contain large quantities of sparkling mica temper. Forms are varied but open lugged vessels are common.	Distinctive blade-based obsidian assemblage.	Highly specialized pastoralism, focus on cattle, sheep, and goats.	(18, 41)
Luxmanda	c. 3,000 cal BP	Savanna Pastoral Neolithic (SPN)	Highland open-air settlement site on the Mbulu Plateau, north-central Tanzania. Largest-known and most southern of all PN settlement sites.	“Narosura” ceramics; vessels are commonly black and exhibit decorative motifs made by comb-stamping or incising, found in bands beneath rims. Forms are typically open bowls in a range of sizes.	Diverse chert, quartz, and obsidian SPN lithics. Bone and ivory tools and ornamentation, groundstone artifacts.	Highly specialized pastoralism, focus on sheep, goat, and cattle.	(26, 37, 42, 43)