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Research Article

Isotopic evidence of an environmental shift at the fall of the Kushite kingdom of Meroë, Sudan

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Between *c*. 300 BC and AD 350, the Meroitic kingdom dominated the Middle Nile Valley; following its breakdown, it was replaced by a series of smaller successor polities. Explanation for this change centres on socio-political and economic instability. Here, the authors investigate the role of climate and environment using stable carbon and oxygen isotope analyses of human and faunal dental enamel from 13 cemeteries. The results show increasing $\delta^{18}O$ values towards the end of the Meroitic kingdom and in the post-Meroitic period, combined with less negative $\delta^{13}C$ values. These trends suggest a shift towards more arid conditions associated with changes in agricultural practices and land use that may have contributed to the kingdom's dissolution.

Keywords: Sudan, Upper Nubia, Meroitic kingdom, isotope analysis, climate change, collapse

Introduction

Kush was one of several early states that formed along the Middle Nile, flourishing for centuries until its fall towards the end of the Meroitic period (*c*. 300 BC–AD 350; Török 1997; Edwards 1998). Archaeological evidence has been used to delimit the extent of the Meroitic kingdom, extending south of the First Nile Cataract (southern Egypt) and encompassing the confluences of the White Nile, Blue Nile and the Atbara River in Sudan (Figure 1; Eisa 1999; Edwards 2004). While the actual boundaries of the kingdom remain a matter of speculation (Lohwasser 2014), however, its focus was the Nile and its tributaries on which its population was dependent. Agricultural advances—including the adoption of the animal-powered waterwheel (*saqia*) and the development of a system of water dams and reservoirs

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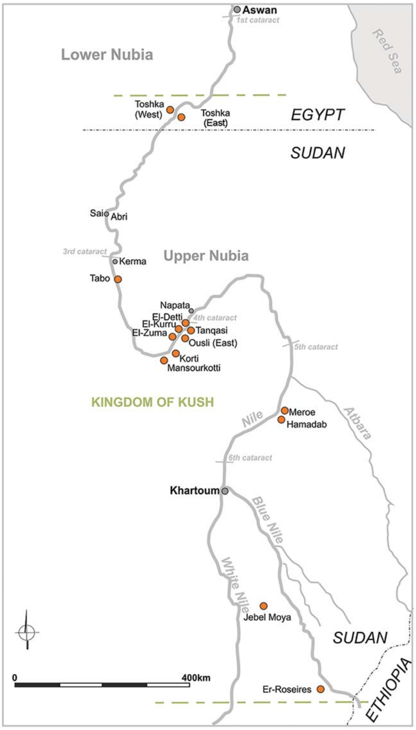

Figure 1. Map of Sudan showing approximate northern and southern limits of the Kushite kingdom and sites mentioned in the text (figure by authors).

(*hafirs*)—facilitated the expansion of plant cultivation, including the use of fields located further from the Nile and large-scale livestock farming (Ehret 2001; Fuller 2014), pushing settlement into new geographical and environmental zones (Edwards 1996, 2004; Edwards & Fuller 2005).

Factors such as geo-political and economic instability and social unrest have long been considered as prime contributors to the collapse of the Meroitic kingdom in the mid-fourth century AD (Török 1988). The extent to which external and/or internal factors contributed to the state's disintegration remains the subject of debate and warrants further research, including assessment of the impact of changing regional climate and environment (Fuller 2014, 2015). Over millennia in the Nile Valley, climate and environmental changes have influenced patterns of human settlement, mobility and the development of complex cultures and technologies that aided adaptation and sustainability (Nicoll 2004; Butzer 2012; Honegger & Williams 2015). Episodes of climate variability and environmental shifts have been linked to episodes of severe drought, famine and state collapse (Touzeau *et al.* 2013, 2017; Welc & Marks 2014; Manning *et al.* 2017).

Stable isotope analysis of bioarchaeological remains can facilitate the identification of environmental and climate change. To date, only a few such studies have provided insights into the environmental conditions during the Meroitic (*c.* 300 BC–AD 350) and post-Meroitic periods (AD 350–550; e.g. Iacumin *et al.* 1996, 2016; White *et al.* 2004). With the aim of determining environmental conditions and their potential contribution to the decline and collapse of the Meroitic state, this article presents new carbon and oxygen isotope data from human and faunal remains from multiple sites in the Middle Nile Valley.

Available proxy records indicate a wetter climate in this region during the first millennium BC and a shift towards increasingly drier conditions thereafter (Machado *et al.* 1998; Williams 2009: 10–11). We hypothesise that this latter climatic shift should be reflected in higher carbon and oxygen isotope values in the late Meroitic and post-Meroitic samples caused by an increase in the consumption of C_4 plants, which are better adapted to drier conditions ($\delta^{13}C$), and a decrease in the amount of precipitation and/or an increase in regional temperatures ($\delta^{18}O$).

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Stable carbon and oxygen isotope analysis in the Nile valley

Stable carbon and oxygen isotope analysis is commonly used for the investigation of mobility, diet and climate change in the Nile Valley (Iacumin *et al.* 1996, 2016; Dupras & Schwarcz 2001; White *et al.* 2004; Buzon & Bowen 2010). The analysis relies on the isotopic signatures recorded in human and animal tissues, such as bone and teeth, which may reflect the isotopic characteristics of the water and the types of plants directly or indirectly consumed, thus providing data about prevailing environmental conditions (Iacumin *et al.* 2016: 500).

Carbon isotope ($\delta^{13}C$) ratios of tooth enamel carbonate reflect the isotopic composition of the dietary carbon sources consumed by an individual during childhood when teeth are forming. Carbon is assimilated by plants through one of three photosynthetic pathways—C_3, C_4 and CAM (Crassulacean Acid Metabolism)—resulting in distinct $\delta^{13}C$ values for each group of plants typically endemic to different types of environments (Bender 1971; Smith & Epstein 1971). For example, plants from temperate regions that follow the C_3 photosynthetic pathway—wheat, barley, most fruits and vegetables—show values of approximately –28‰ to –26‰ (VPDB, Vienna Pee Dee Belemnite international standard for carbon isotopes). C_4 plants, typically endemic to hot and arid environments (e.g. sorghum and millet), demonstrate higher values of approximately –14‰ to –12‰ (VPDB). Archaeological evidence indicates that the ancient dietary regime in the Nile Valley was a mix of C_3 and C_4 sources, with the former being dominant. Sorghum, a C_4 plant found sporadically in the third-millennium BC deposits (Brass *et al.* 2019), was widely incorporated into diet by the Meroitic period (Rowley-Conwy 1989). The significant increase in the consumption of C_4 plants previously observed during the post-Meroitic period (White & Schwarcz 1994; Fuller & Lucas 2021) could reflect changes in the types of cultivated crops dictated by increasing aridity. Previous stable isotope analysis has identified periods where an increase in the consumption of C_4 plants corresponds with low Nile water levels and episodes of social unrest (e.g. Iacumin *et al.* 1998; Thompson *et al.* 2005, 2008; Turner *et al.* 2007; Touzeau *et al.* 2013). For example, Iacumin *et al.* (2016) found changes in subsistence strategies in the Middle Nile Valley dictated by changing environmental conditions between the Pre-Mesolithic (>7000 BC) and Meroitic period (fourth century BC–fourth century AD).

Oxygen isotopes are available to humans and animals from a variety of sources, including the atmosphere, food and drinking water, with the latter being the most significant contributor to oxygen intake (Luz *et al.* 1984). For communities settled along the Nile valley, including all the individuals discussed below, the primary source of water for consumption and irrigation was the river (rather than ground water accessed via wells); the local $\delta^{18}O$ values of the river water should therefore be reflected in the oxygen isotope ratios in the mineralised tissues of humans and animals living in the region (White *et al.* 2004). Oxygen isotope values in water vary regionally due to a combination of factors—hydrological, geographical and climatological (Gat 1996)—which can therefore be used as a proxy for palaeoclimatic conditions and mobility (e.g. Buzon & Bowen 2010). In surface water, such as the Nile, these values vary directly with temperature fluctuation and the effects of precipitation and evaporation, providing a reliable record of local climate. Temporal variation of regional $\delta^{18}O$ values may represent a shift in climatic conditions, as demonstrated by Touzeau *et al.* (2013, 2017),

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with the values increasing as one moves north along the Nile due to the preferential loss of ^{16}O in river water caused by evaporation.

Modern $\delta^{18}O$ values of Nile River water vary between −5.7‰ in rainy season flows in the Blue Nile and +2‰ to +4‰ (VSMOW, Vienna Standard Mean Ocean Water) at the Nile delta (Buzon & Bowen 2010). Precipitation in the areas north of 18°N (Nubia) is negligible but increases gradually to the south; in Khartoum (15°N), modern records (1961–2009) indicate average annual rainfall of 155.7±69.6mm during the summer months (June to October), with rainwater averaging annual $\delta^{18}O$ values of −0.93‰ (IAEA/WMO n.d).

Materials and methods

This study reports isotopic analyses on 64 dental enamel samples collected from 56 human individuals recovered from 13 cemeteries (Figure 1 & Table 1), including 10 recently excavated sites. Eight Meroitic and post-Meroitic cemeteries—all near the Nile—are located between the Third and Fourth Cataracts and a further two are downstream from the Sixth Cataract. The main study assemblage (n=58) includes 11 early Meroitic (300 BC–AD 90), 10 Meroitic (300 BC–AD 350), 14 late Meroitic (AD 90–350) and 23 post-Meroitic (AD 350–500) samples; below, these are treated as four temporal subsets. For comparative purposes, we also analyse additional samples: two inhumations from Toshka associated with the Bronze Age C-Group culture (*c.* 2400–1550 BC) and one contemporaneous inhumation from Jebel Moya, plus a further three inhumation burials from medieval (AD 550–1500) and post-medieval (AD 1500–1900) contexts at Er-Roseire and Hamadab, respectively. In addition to human samples, isotope ratios in samples (n=15) of bovids, ovicaprids and one canid associated with the post-Meroitic burials at El-Zuma and El-Detti are also analysed, primarily for context (online supplementary material (OSM) Table S1).

To avoid the effects caused by $\delta^{18}O$ enrichment through breast-milk consumption (Roberts *et al.* 1988), enamel samples were collected primarily from post-weaning teeth (M2 and M3), with canines and premolars as substitutes where necessary; in the latter case, samples were taken from the lower parts of the crown that form after weaning at approximately five years and over.

Powdered samples were flushed with helium (He), then five drops of water-free orthophosphoric acid (H_3PO_4) were added. Following reaction with H_3PO_4 and chromatographic isolation of carbon dioxide (CO_2) on a Gasbench II automated preparation device, the carbon and oxygen composition of hydroxyapatite carbonate was analysed using a Thermo-Fisher MAT253 Isotope Ratio Mass Spectrometer. Both $\delta^{13}C$ and $\delta^{18}O$ values are reported relative to the VPDB standard (standard deviations of ≤0.05‰ and ≤0.02‰, respectively). The datasets were analysed using non-parametric tests with STATISTICA software package (StatSoft, USA version 13). The cultural chronologies of the 11 cemeteries from which the samples were obtained are verified with radiocarbon dating (see Table S2).

Results

The $\delta^{13}C$ and $\delta^{18}O$ measurements (Table S1) are pooled according to discrete time periods (Table 2) to determine temporal trends in the isotopic values. Figure 2 shows the temporal

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Table 1. Summary of sources of human and faunal samples.

Site	Latitude, Longitude	Cultural Period	N_h	N_a	References
El-Detti	18°25′27.41″N 31°46′33.67″E	Post-Meroitic	4	4	El-Tayeb *et al.* 2016; Iwaszczuk 2016
El-Kurru	18° 24′ 36″N, 31° 46′ 17″E	Meroitic	2	–	Reisner 1920; Dunham 1950
Er-Roseires	11° 52 ′01.1″N 34° 23′ 30.6″E	Medieval	1	–	–
El-Zuma	18°22′09.69″N 31°44′ 19.31″E	Post-Meroitic	16	12	El-Tayeb *et al.* 2016; El-Tayeb & Czyżewska-Zalewska 2020
Hamadab	16° 54′ 42″N 33° 41′ 31″E	Meroitic	8	–	Wolf 2015; Wolf *et al.* 2014
Hamadab	16° 54′ 42″N 33° 41′ 31″E	Post-Medieval	2	–	–
Jebel Moya	13° 30′ 0″N 33° 20′ 0″E	Contemporaneous with C-Group	1	–	Brass *et al.* 2019, 2020
Korti (DDASP DS128)	18° 05′ 4.4″N 31° 35′ 48″E	Late Meroitic	6	–	Abdelsawi 2019
Mansourkotti (DDASP DS2)	18° 02′ 0.1″N 31° 20′ 01″E	Late Meroitic	6	–	Hassan Bakheit 2015, 2016
Meroë (Begrawiya)	16° 56′ 15.6″ N 33° 44′ 56″ E	Post-Meroitic	1	–	–
Ousli (East) (DDASP DS231)	18° 12′ 10.8″N 31° 41′ 5.7″E	Late Meroitic	3	–	Abdelsawi 2019
Tabo	19° 29′ 5″N, 30° 25′ 36″E	Early Meroitic	11	–	Maystre 1969
Tanqasi	18° 23′ 37.8″N 31° 49′ 0.6″E	Late Meroitic–Post-Meroitic	3	–	Wyżgoł & El-Tayeb 2018
Toshka*	22° 42′ 22″N, 32° 01′ 56″E	C-Group	2	–	Junker 1926

N_h – number of human samples; N_a – number of faunal samples.
* Approximate location – submerged by Lake Nasser.

Table 2. $\delta^{13}C$ and $\delta^{18}O_{ca}$ (ca=tooth carbonate) values in human enamel carbonates and animal samples.

Chronology		n	$\delta^{13}C$ (‰,VPDB) median	mean	SD	$\delta^{18}O_{ca}$ (‰,VPDB) median	mean	SD
C-Group (2400–1550 BC)		3	-9.18	-8.22	2.82	1.31	1.22	0.30
Early Meroitic (300 BC–AD 90)		11	-7.40	-6.93	1.98	-0.08	0.02	2.34
Meroitic (300 BC–AD 350)		10	-3.96	-5.87	4.52	-1.11	-1.10	1.29
Late Meroitic (AD 90–350)		14	-4.27	-4.39	1.45	1.29	0.37	2.21
Post-Meroitic (AD 350–550)		23	-4.87	-5.05	2.01	1.30	0.93	1.85
Medieval (AD 550–1500) and post-medieval (1500–1900)		3	-4.36	-4.90	1.98	-2.99	-2.45	1.64
Animal samples	bovids	7	-1.38	-1.60	2.11	4.76	5.18	2.05
Post-Meroitic	ovicaprids	7	-4.81	-4.76	1.74	3.72	2.87	2.94
	canid	1		-7.10			4.61	

distribution of the $\delta^{13}C$ and $\delta^{18}O$ values in human tooth enamel samples. When the outliers are removed (two individuals from El-Kurru with exceptionally low $\delta^{13}C$ values and one individual from Tabo with the highest $\delta^{18}O$ value), the differences in $\delta^{13}C$ values between the four Meroitic

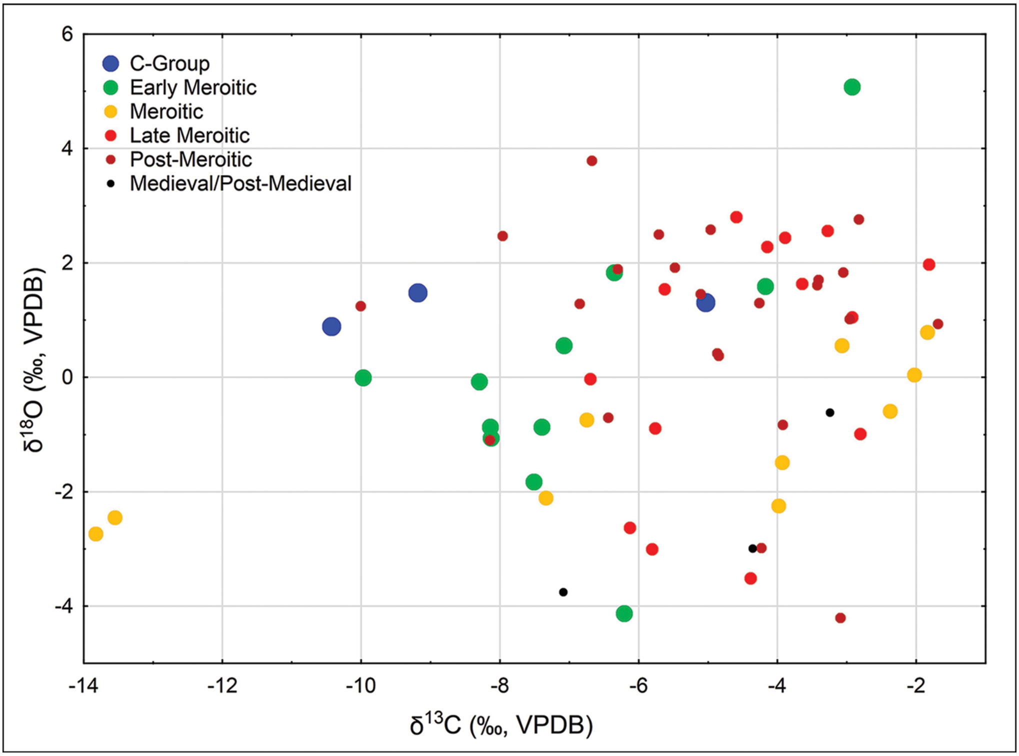

Figure 2. Scatter plot of $\delta^{13}C$ and $\delta^{18}O_{ca}$ (ca=tooth carbonate) values for samples from the six temporal subsets (figure by authors).

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subsets are statistically significant (Kruskal-Wallis test, N=55, H=15.10, p=0.0017) and the post-hoc pairwise comparison indicates a statistically significant difference between the early Meroitic (the lowest $\delta^{13}C$ values) and the subsequent subsets (Figure 3).

The distributions of the $\delta^{18}O$ values in the early Meroitic and Meroitic subsets roughly follow a normal distribution with the mode close to −1‰, but in the late Meroitic and post-Meroitic subsets it is left-skewed with the mode close to 2‰ (Figure 4). As the distributions of the $\delta^{18}O$ values in the early Meroitic and Meroitic subsets are similar, these two subsets are combined. The temporal differences in the $\delta^{18}O$ values between the three resulting periods —early Meroitic/Meroitic, late Meroitic and post-Meroitic—are statistically significant (Kruskal-Wallis test, N=55, H=8.24, p=0.016), mainly due to the difference between the Early Meroitic/Meroitic and post-Meroitic subsets (post-hoc pairwise comparison p=0.014). The difference in the $\delta^{18}O$ values between the early Meroitic/Meroitic and late Meroitic subsets is not statistically significant (p=0.095) due to the small sample size; nevertheless, the distribution of the $\delta^{18}O$ values in the late Meroitic subset follows the same pattern as in the post-Meroitic subset (Figure 4). The C-Group and medieval/post-medieval subsets are too small to be included in the statistical analysis; however, they demonstrate a pattern of continuity (particularly in the $\delta^{13}C$ values) between the Bronze Age and the

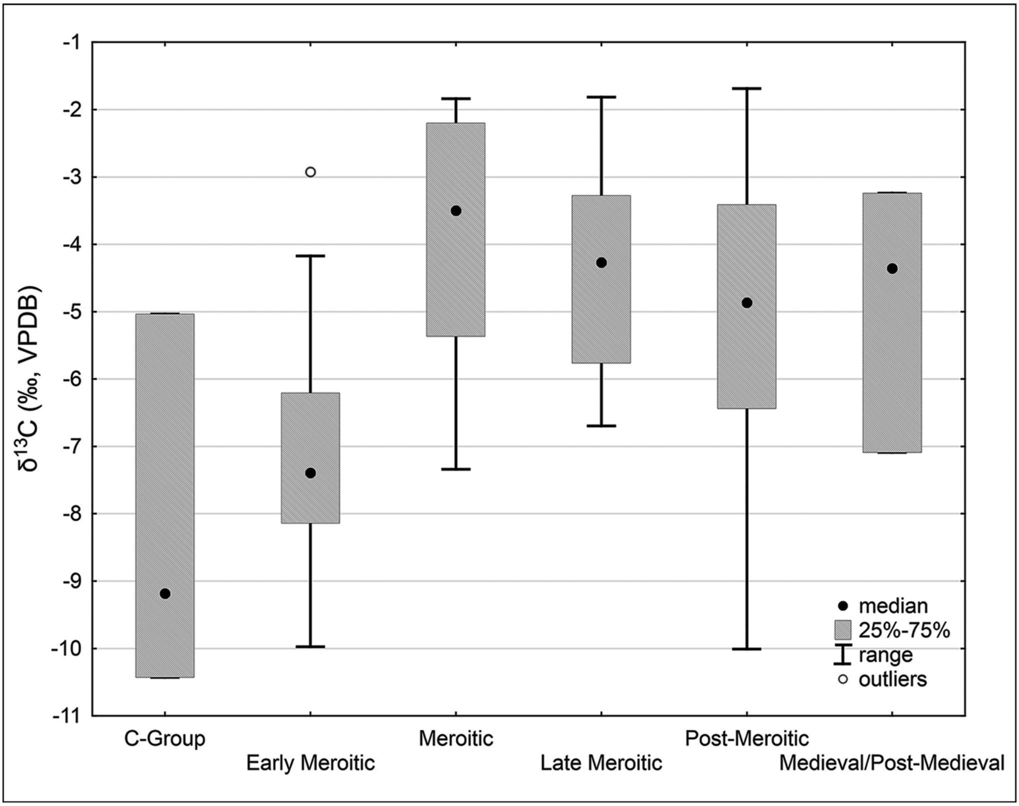

Figure 3. Boxplot showing the temporal pattern in $\delta^{13}C$ values (figure by authors).

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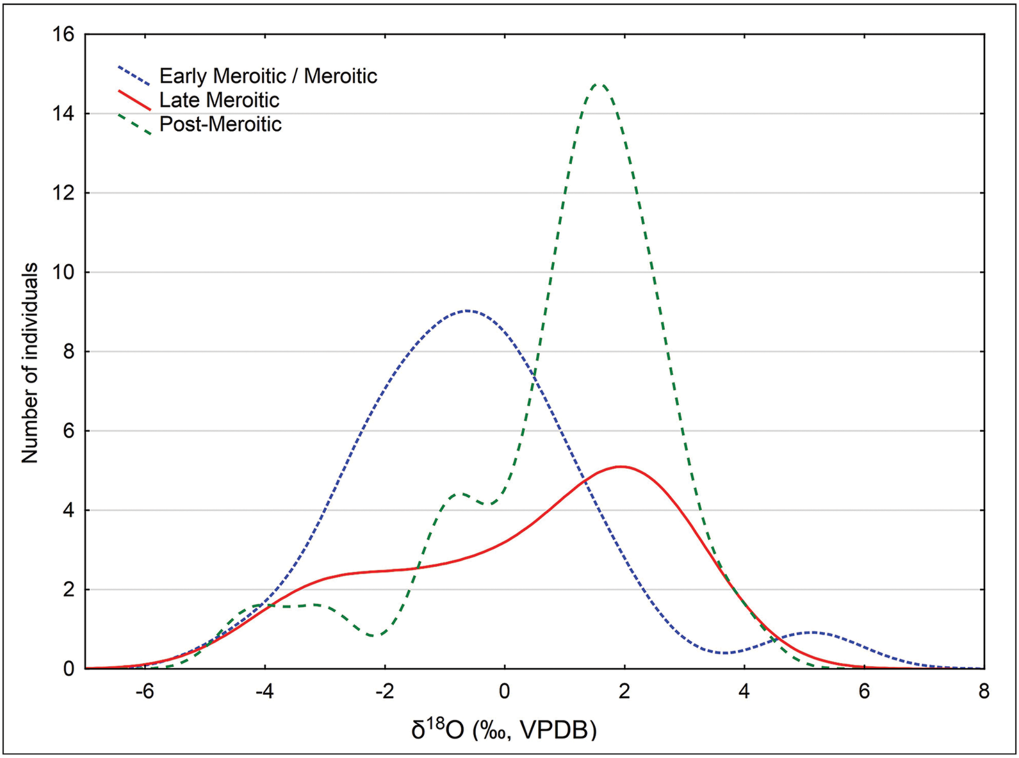

Figure 4. Gaussian kernel density distribution of $\delta^{18}O_{ca}$ (ca=tooth carbonate) in three temporal (figure by authors).

early Meroitic period, with a decrease in the δ^{18}O values between the post-Meroitic and medieval/post-medieval periods (see Figure 2).

Due to the small sample size, the differences in the δ^{13}C and δ^{18}O values between males and females can only be tested for the combined late Meroitic and post-Meroitic subsets. The differences in the δ^{18}O values of males and females is not significant (Mann Whitney U-test, Z=−1.15); however, the average δ^{13}C value of females is significantly higher than in males (Mann Whitney U-test, n(f)=16, N(m)=24, Z=2.28, p=0.023) and the variability is lower in females (median –4.25‰, mean –4.23‰, SD=0.99‰) than in males (median –5.47‰, mean –5.45‰, SD=1.92‰).

Next, the post-Meroitic human dataset is compared with contemporaneous faunal data from bovids and ovicaprids (Figure 5). When one outlier (an ovicaprid) is excluded, the average δ^{13}C and δ^{18}O values are higher in animals than in humans. In bovids, two relatively distinct clusters can be observed: one overlapping the distribution of the δ^{13}C and δ^{18}O values in ovicaprids and one with distinctly higher δ^{13}C and δ^{18}O values. The difference in the δ^{13}C values between humans and bovids is statistically significant (Kruskal-Wallis test, n=36, H=10.61, p=0.005; post-hoc pairwise comparison p=0.0034). In the δ^{18}O values, humans differ significantly from both bovids and ovicaprids (Kruskal-Wallis test, n=36, H=20.17, p<0.0001; post-hoc pairwise comparisons p=0.00031 and p=0.0069, respectively).

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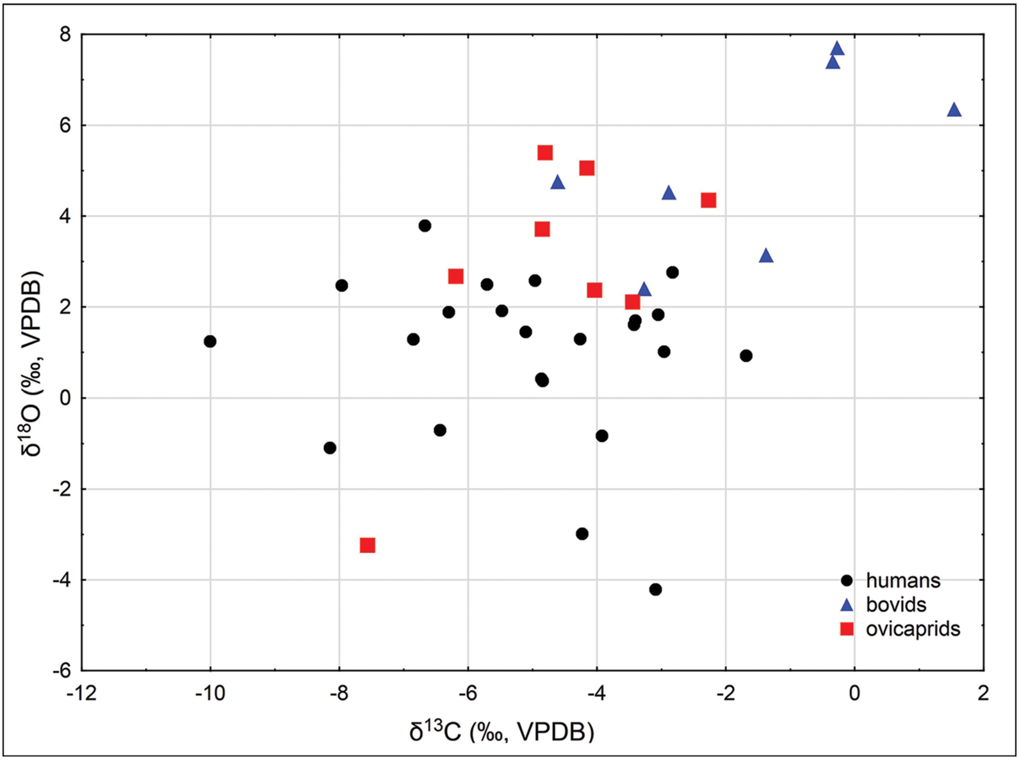

Figure 5. Scatterplot of $\delta^{13}C$ and $\delta^{18}O_{ca}$ (ca=tooth carbonate) values in humans, bovids and ovicaprids in the post-Meroitic period (figure by authors).

Discussion

The isotopic analysis of human enamel samples from sites in Upper Nubia (Third to Sixth Cataracts) reveals an upward shift in the $\delta^{13}C$ values following the early Meroitic period. This result indicates a progressive dietary shift towards greater consumption of C_4 plants (sorghum and millet) and reduced consumption of C_3 crops (wheat and barley). These findings corroborate previous isotopic studies conducted on human hair samples from Lower Nubia (First to Second Cataract) that found a marked shift towards a greater consumption of C_4 plants and agricultural bi-seasonality in the post-Meroitic Period (Schwarcz & White 2004; Fuller & Lucas 2021). The data presented here for Upper Nubia are not directly comparable with those from Lower Nubia because they are based on different tissues (tooth enamel versus hair, White & Schwarcz 1994). Notwithstanding, data from the present study strongly suggest that the dietary shift from C_3 to C_4 plants occurred over a significantly larger geographical region than previously believed.

Archaeobotanical evidence from Meroitic settlements attests to the presence of sorghum and the practice of double-cropping—a system combining the cultivation of winter (wheat and barley) and summer (sorghum, cowpea, hyacinth bean) crops (Fuller 2004, 2014). The latter are sown during the Nile low water season; the introduction of irrigation systems

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permitted the expansion of the cultivation of these crops northwards beyond the savannah zone and on to land further away from the Nile floodplain. In contrast to the Meroitic heartland, the cultivation of summer crops in Lower Nubia was insignificant until the third and fourth centuries AD when *saqia* irrigation was introduced. This development created more arable land and supported the cultivation of such crops during annual low Nile water season and during periods of low flood levels, likely probably caused by fluctuation in temperature and reduced precipitation.

This agricultural shift, characterised by intensification of the cultivation of summer crops, may be attributed to contemporaneous climate change, reduced precipitation and increasing aridity in the region (Machado *et al.* 1998). The isotopic data presented here show a clear temporal shift in the $\delta^{18}O$ values between the early Meroitic, late Meroitic and post-Meroitic periods, correlating with the palaeoclimatic data, which suggest lower rainfall in Ethiopia—and by extension in Sudan—during the first centuries AD. The data collected in this study come from individuals who lived near the Nile and its water would have been their main source for irrigation, cultivation and consumption. This is supported by the presence of *hafirs*—water-catchment basins—identified at several Meroitic sites, for example Meroë-Begrawiya, Musawwarat es-Sufra and Naga (Berking *et al.* 2010; Berking & Schütt 2018). This water-harvesting technique, introduced during the Meroitic period, allowed for the capture and long-term retention of water following the rainy season and/or seasonal flooding of the Nile, and it remains in use in modern-day Sudan.

The different sources of water consumed by humans have implications for all isotopic studies because the ratios of oxygen isotopes differ between surface and ground water and may be affected by methods of water storage and food preparation. In the present context, however, there is broad evidence for the use of surface water for irrigation and consumption; therefore, the temporal differences in the $\delta^{18}O$ values most probably reflect a progressive decline in precipitation due to climate change.

The expansion of agricultural areas and intensification of crop cultivation were instrumental in supporting permanent settlements and stimulating population growth; in turn, these developments may have caused the overexploitation of the limited arable land available and conflict with pastoralists over access to land. The higher $\delta^{13}C$ and $\delta^{18}O$ values in the post-Meroitic faunal samples compared with the contemporaneous human isotope values suggest that animals were kept at a distance from the Nile settlements and grazed on primarily C_4 grasses and shrubs typically found in semi-desert or dry savannah pastures. The isotopic diversity observed for the two bovid groups—one with values similar to the ovicaprids, the other with distinctively higher values—could be interpreted as evidence of distinct herding strategies and landscape exploitation during the post-Meroitic period, possibly in response to environmental pressures. The narrow strip of arable land along the Nile would have been reserved for the cultivation of crops for human consumption and crop waste used as fodder for the animals kept nearby (the ovicaprids and bovids with similar isotopic values), whereas mobile herding would have taken place in drier environments away from the Nile (as suggested by the bovids with higher isotopic values).

The (progressively) higher $\delta^{13}C$ values in humans towards the post-Meroitic period probably reflect a dietary shift towards C_4 plants and cereals and/or the products of C_4-plant-eating animals (Iacumin *et al.* 1998). The data reveal that the post-Meroitic sub-sample shows a

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great range of $\delta^{13}C$ values in comparison to the Meroitic sub-samples (Figure 3). This is due to a small number (4/23, 17.4%) of outliers—all males—with either higher (–1.68) or lower (–7.96, –8.14, –10.00) $\delta^{13}C$ values than the standard range (–6.85 to –2.82) observed for the period (Table S1). Overall, the late/post-Meroitic sub-sample demonstrates a difference in average $\delta^{13}C$ values between males and females, with the former lower than the latter. Considering local $\delta^{18}O$ values for the post-Meroitic male outliers, the observed difference in average $\delta^{13}C$ values between males and females could suggest a gender-based difference in diet among sub-adults (when teeth are forming), with higher C_4-plants intake in females. Further insights into individual dietary practices can be observed by comparing $\delta^{13}C$ values obtained from teeth that form at different life stages. For instance, differences in $\delta^{13}C$ values recorded in the canine and third molar in two of the male outliers (El-Zuma T.9 & T.27; Table S1) may indicate age-based (early childhood versus late childhood/early adolescence) differences in diet; alternatively, they could indicate periods of environmental stress that led to a temporary shortage of one plant group and a reliance on the other (e.g. stored grain), leading to a downward or upward shift in $\delta^{13}C$ values (diet either enriched or depleted in C_4 plants). These observations warrant further investigation into the dietary practices of the period.

Conclusions

In this article, we have presented new isotopic data sourced from 13 cemeteries along the Nile in Upper Nubia finding evidence for higher $\delta^{13}C$ and $\delta^{18}O$ values during the post-Meroitic period that indicate greater consumption of C_4 plants and an increase in aridity. These findings reinforce the existing palaeoclimatic and proxy data on climate and environmental changes that affected Nubia and the wider region in the first centuries AD (e.g. McCormick *et al.* 2012). Palaeopathological data from the region (Davies-Barrett *et al.* 2021) reflect the impact of progressive aridification on humans and support the hypothesis of an environmental shift. The interplay of environmental, political, socio-cultural and demographic factors, including intensification of agricultural practices, population growth and urbanisation, was instrumental in the decentralisation and dissolution of the Meroitic kingdom. Changing climate and environment likely acted as a catalyst for the socio-political transformation that culminated in the cessation of centralised power in favour of smaller splinter states (Fuller 1997, 2003, 2014). A series of such successor states formed during the post-Meroitic period, later replaced by Christian kingdoms that dominated the territory of the former Meroitic kingdom (Török 1988; Edwards 2004).

More broadly, by adding to the body of isotopic data from Meroitic and post-Meroitic Nubia, this study contributes to the wider debate on past climate–society interactions (e.g. Degroot *et al.* 2021; Biagetti *et al.* 2022). Such insights into the complexity of climate–society interactions inform studies of human resilience and of adaptation strategies to changing environmental conditions, past and present.

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Supplementary information

To view supplementary information for this article, please visit https://doi.org/10.15184/aqy.2023.162.

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