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Palaeontology

Ecological change in the lower Omo Valley around 2.8 Ma

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Late Pliocene climate changes have long been implicated in environmental changes and mammalian evolution in Africa, but high-resolution examinations of the fossil and climatic records have been hampered by poor sampling. By using fossils from the well-dated Shungura Formation (lower Omo Valley, northern Turkana Basin, southern Ethiopia), we investigate palaeodietary changes in one bovid and in one suid lineage from 3 to 2 Ma using stable isotope analysis of tooth enamel. Results show unexpectedly large increases in C_4 dietary intake around 2.8 Ma in both the bovid and suid, and possibly in a previously reported hippopotamid species. Enamel $\delta^{13}C$ values after 2.8 Ma in the bovid (*Tragelaphus nakuae*) are higher than recorded for any living tragelaphin, and are not expected given its conservative dental morphology. A shift towards increased C_4 feeding at 2.8 Ma in the suid (*Kolpochoerus limnetes*) appears similarly decoupled from a well-documented record of dental evolution indicating gradual and progressive dietary change. The fact that two, perhaps three, disparate Pliocene herbivore lineages exhibit similar, and contemporaneous changes in dietary behaviour suggests a common environmental driver. Local and regional pollen, palaeosol and faunal records indicate increased aridity but no corresponding large and rapid expansion of grasslands in the Turkana Basin at 2.8 Ma. Our results provide new evidence supporting ecological change in the eastern African record around 2.8 Ma, but raise questions about the resolution at which different ecological proxies may be comparable, the correlation of vegetation and faunal change, and the interpretation of low $\delta^{13}C$ values in the African Pliocene.

1. Introduction

Four decades of research have addressed the nature and magnitude of environmental change on faunal evolution in Africa in the late Pliocene and early Pleistocene. A major impediment to investigation has been a lack of well-dated fossiliferous and sedimentary sequences that continuously sample the 3–2 Ma period and that could be precisely compared with global palaeoclimate proxy records. Under the framework of the Omo Group Research Expedition [1], we here explore palaeoecological change in Plio-Pleistocene eastern Africa using dietary investigation of well-studied, phylogenetically evolving herbivore species lineages across the 3–2 Ma period.

The suid *Kolpochoerus limnetes* and the bovid *Tragelaphus nakuae* (with its immediate ancestor *Tragelaphus rastafari*) are phylogenetically evolving species lineages that are well represented and well studied in Plio-Pleistocene deposits

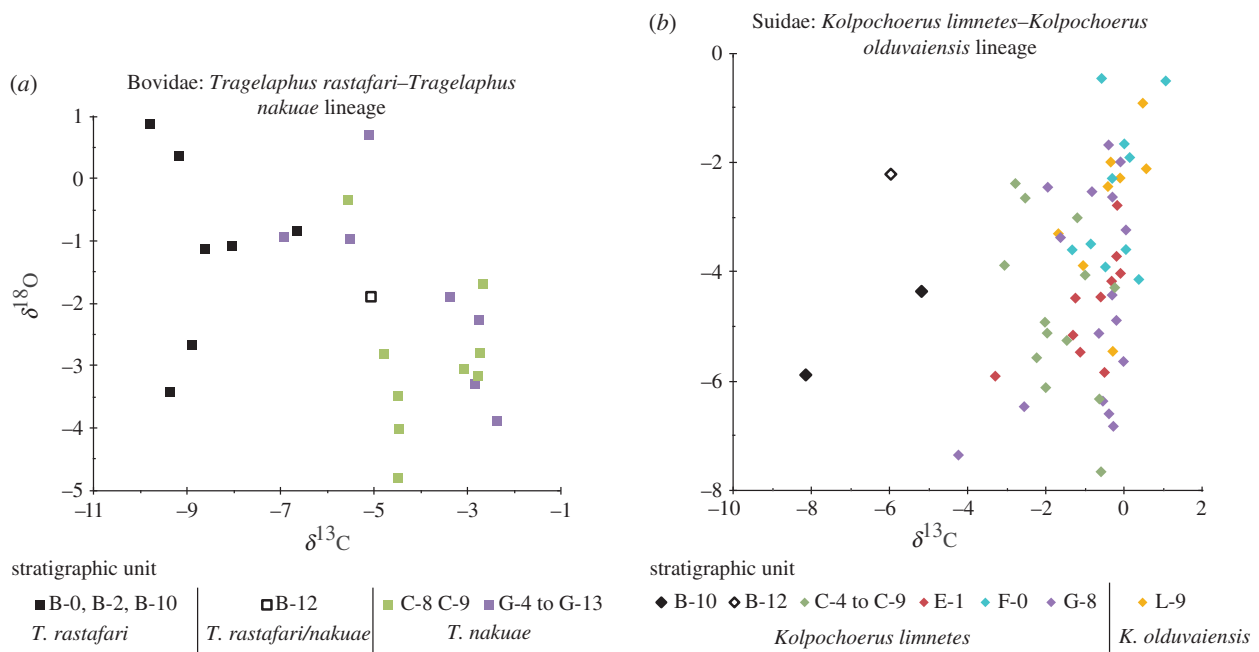


Figure 1. Enamel $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values for the fossil (a) bovid and (b) suid specimens sampled. These are differentiated by stratigraphic level within the Shungura Formation. Specimens from units C-4 and younger (i.e. $< \sim 2.8$ Ma) are significantly enriched in $\delta^{13}\text{C}$ relative to those from units B-10 and older.

of eastern Africa [2–5]. We used precisely dated fossils of these lineages from the Shungura Formation in the lower Omo Valley (northern Turkana Basin, southern Ethiopia), which provides the single most continuous and best-dated fossiliferous sequence of the 3–2 Ma time period anywhere in Africa. We measured tooth enamel stable carbon and oxygen isotope ratios in order to determine whether any significant dietary changes had occurred that might be correlated with local, regional or global palaeoenvironmental signals. We also refer to enamel isotope values for two specimens of the hippopotamid aff. *Hippopotamus protamphibius* reported by Souron *et al.* [6].

2. Material and methods

Twenty-four bovid and 60 suid specimens were sampled at the Authority for Research and Conservation of Cultural Heritage in Addis Ababa. Around 20 mg of fossil enamel from each specimen was treated with buffered acetic acid and reacted with anhydrous H_3PO_4 , with the resulting CO_2 analysed using a Finnigan MAT 252 isotopic ratio mass spectrometer. Stable carbon and oxygen isotope ratios are reported as δ -values relative to the Vienna Pee Dee Belemnite (VPDB) standard using permil (‰) notation, where $\delta^{13}\text{C} = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$; R_{sample} and R_{standard} are the $^{13}\text{C}/^{12}\text{C}$ ratios (or $^{18}\text{O}/^{16}\text{O}$ ratios in the case of $\delta^{18}\text{O}$) in the sample and in the standard, respectively, and the $\delta^{13}\text{C}$ (or $\delta^{18}\text{O}$) value of VPDB is defined as 0‰. Full details on materials and methods can be found in the electronic supplementary material.

3. Results

Enamel $\delta^{13}\text{C}$ values in the Shungura bovid, suid and hippopotamid studied became more enriched by an average +4‰ between units B-10 and C-4/C-5, or sometime between 2.97 Ma and just under 2.74 Ma (figures 1 and 2) [7]. $\delta^{18}\text{O}$ values, while showing some changes in the mean and variances among the different stratigraphic levels (especially in

the suids), do not show the type of directional change observed in the $\delta^{13}\text{C}$ data. Full results can be found in the electronic supplementary material.

4. Discussion

We record a pronounced increase in enamel $\delta^{13}\text{C}$ around 2.8 Ma in both the bovid and suid lineages studied (figure 1). Although only two Shungura hippopotamid specimens were sampled by Souron *et al.* [6], the timing, direction and magnitude of the change in enamel $\delta^{13}\text{C}$ match those of the bovid and suid. Such large (greater than +4‰) increases in $\delta^{13}\text{C}$ indicate significantly increased dietary intake of C_4 plant resources in a relatively short time frame, or not more than (and perhaps much less than) 300 000 years (figure 2). In the bovid lineage, the $\delta^{13}\text{C}$ shift is contemporaneous with a recently recognized taxonomic boundary between chronospecies *T. nakuae* (younger than around 2.8 Ma) and *T. rastafari* (older than 2.8 Ma) [3]. However, taxonomic differentiation was made mainly on the basis of braincase morphology, with no obvious indications of any dentognathic changes that might suggest a change in dietary behaviour. Enamel $\delta^{13}\text{C}$ values in *T. nakuae* are also higher than recorded among living tragelaphin species [11], but the significance of this is difficult to interpret without related dental wear data (see the electronic supplementary material, section discussion).

Findings for mixed feeding or grazing behaviours in the suid and hippopotamid are not unexpected given the dietary preferences of these animals today, as well as their dental morphologies, which permit an abrasive and grass-based diet. What is surprising is the rapidity of the dietary shift implied by the $\delta^{13}\text{C}$ data. Dental evolution in *K. limnetes*, such as other suid lineages of the Plio-Pleistocene, is progressive, with gradual lengthening of the third molars, premolar row reduction and increases in hypsodonty and body size indicating long-term adaptation to an increasingly abrasive diet [2,5]. Morphological changes around 2.8 Ma are not especially significant

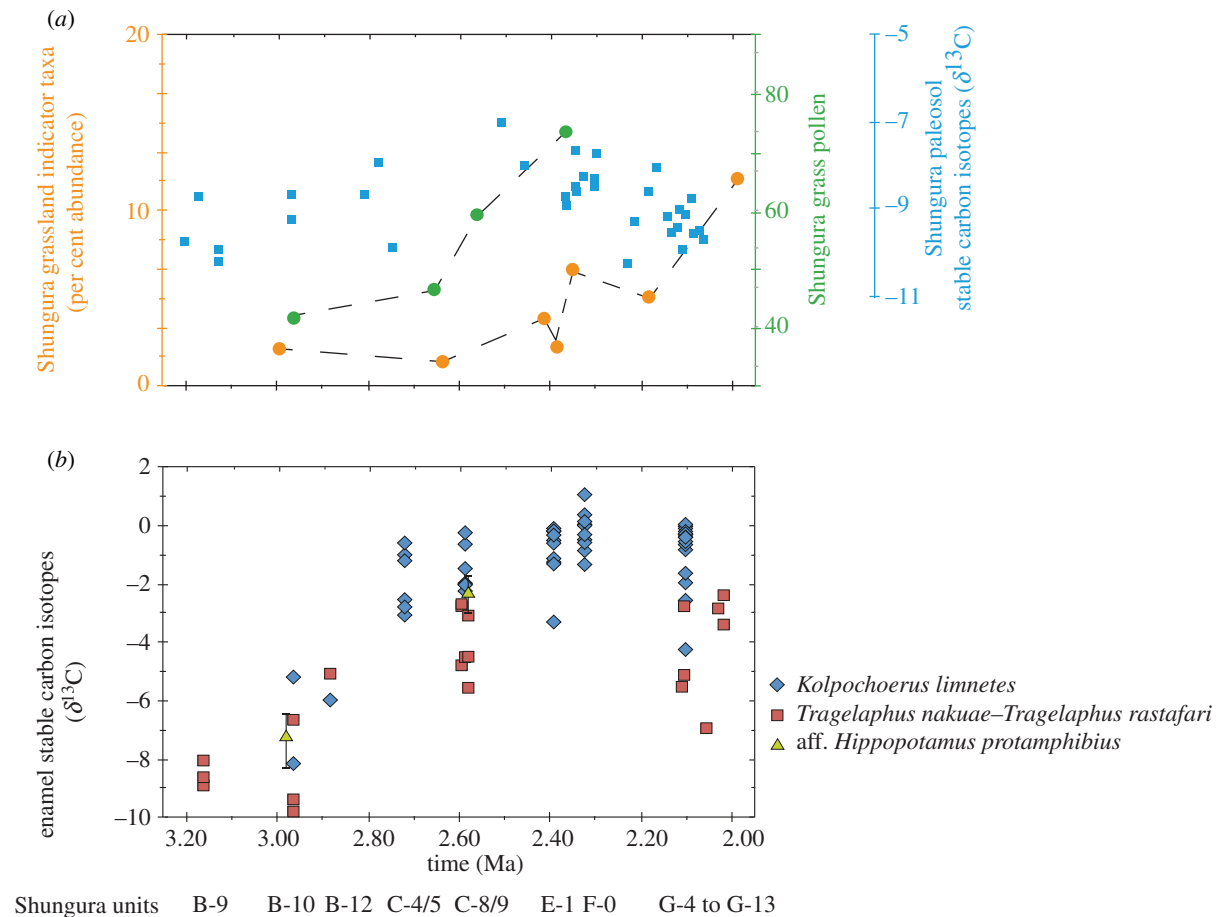


Figure 2. Local palaeoenvironmental indicators in the Shungura Formation from 3.2 to 2.0 Ma. (a) Palaeosol stable carbon isotopes [8], grass pollen percentages [9] and proportions of mammals indicative of secondary grassland habitats [10]. (b) Fossil enamel stable carbon isotopes show a large increase in enamel $\delta^{13}\text{C}$ around 2.8 Ma indicating palaeodietary change. The $\delta^{13}\text{C}$ increase, however, is not correlated with the expansion of grassland habitats and loss of tree cover, or with proportional increases in grazing mammals. Different ecological proxies, however, may be sampling different spatial and temporal scales.

compared with those observed at other times in this lineage's evolution, and our data suggest a major dietary shift at 2.8 Ma that is decoupled from the long and gradual evolutionary progression indicated by the dentognathic morphological data. Like the suid, the *aff. Hippopotamus protamphibius* lineage shows gradual elongation of its third molars over time [12], and a large dietary shift in this lineage, if confirmed by further sampling, would be similarly significant.

Although similar to previously reported $\delta^{13}\text{C}$ increases in late Miocene herbivores [13], exact dietary interpretations for our data and any resulting inferences about the balance of grasslands to woodlands are confounded by evidence that C_3 grasses may have made up a larger proportion of lowland African vegetation biomass during the Pliocene than they do today [14]. In the absence of further data (e.g. dental wear, phytoliths), it is not possible to rule out the presence and exploitation of C_3 grasses in the lower Omo Valley prior to 2.8 Ma. The $\delta^{13}\text{C}$ increase may therefore represent either a significant replacement of trees by grasses (with impacts on herbivore dietary strategies), or a less remarkable replacement of pre-existing C_3 grasses by C_4 grasses (with limited or no change in dietary behaviour). Broader faunal isotopic sampling along with studies of dental wear should be able to further test these scenarios.

That a pronounced increase in dietary $\delta^{13}\text{C}$ took place contemporaneously in two, possibly three, ecologically distinct herbivore lineages opens the possibility of a common environmental driver. Numerous faunal, botanical

and palaeoclimate proxy records have identified 2.8–2.5 Ma as a period of drying in Africa [15–17]. In the Shungura mammalian fossil record, 2.8 Ma coincides with a period of elevated ecological and taxonomic turnover that reflects increased aridity and a reduction in humid-forested environments [10,18]. However, mammalian, pollen and palaeosol isotope records also indicate that habitats in the lower Omo Valley during this time remained relatively mesic with no indications of significant grassland habitat expansion until 2.6 Ma or later (figure 2) [8–10]. Some of these differences might be explained by factors affecting the spatial and temporal scaling of the different proxy methods. For example, the stability of the Omo watershed, which supported mesic riparian environments somewhat buffered against regional aridification that more strongly affected areas peripheral to the river itself [8,10,19], or selective feeding by herbivores that might target rare vegetation types or areas peripheral to the river axis. At face value, however, the raw data suggest that vegetation, faunal and evolutionary responses between 3 and 2.5 Ma in the lower Omo Valley may have been decoupled on the order of 100 ka or more.

Similar analyses should be extended to other African fossil faunas in order to determine whether the $\delta^{13}\text{C}$ increase we record was part of a broader pulse of late Pliocene ecological change or was restricted to the lower Omo Valley. Regional comparisons are currently limited, but the available palaeosol and enamel stable isotope records [8,20–23] from the nearby Nachukui and Koobi Fora formations, while

indicating net increases in aridity and C₄ biomass through time, show no evidence for a large and step-like shift around 2.8 Ma. This suggests that the dietary changes we observe may have been restricted to the lower Omo Valley, providing another example of how these faunas, located within the same depositional basin, differed ecologically.

Neither the rate nor the magnitude of the dietary changes we record (especially in *Tragelaphus*) were to be expected from existing lines of contextual evidence, including dental morphology, faunal turnover, and the palaeosol and palaeobotanical proxy records. Our findings do support previous indications of net change towards increasingly arid habitats in the late Pliocene of eastern Africa, in concert with global and regional climatic records, with the additional indication that major evolutionary responses such as dietary changes,

C₄ grassland expansion, faunal reorganization and functional adaptation may not have been tightly coupled, even within a single depositional basin.

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ELECTRONIC SUPPLEMENTARY MATERIAL

to accompany “Ecological Change in the Lower Omo Valley around 2.8 Ma”

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Materials and Methods

The ratio of carbon 13 to carbon 12 in mammalian herbivore tooth enamel (reported relative to a standard in permil notation as $\delta^{13}\text{C}$) reflects the proportion of C_4 to C_3 plants ingested during tooth enamel mineralization. At tropical latitudes and low elevations today (<1000m asl), C_4 plants are mainly grasses and sedges found in open or dry habitats, while C_3 plants are mainly trees or herbaceous dicots typically found in shaded or humid habitats [1, 2]. The proportion of grasses that are C_3 at low elevations today in Africa is never more than about 10% [2]. C_3 plants in eastern Africa have a mean $\delta^{13}\text{C}$ value of $-27.4 \pm 1.5\text{‰}$ (range of approximately -37 to -23‰), while C_4 plants have a range of -14 to -10‰. After ingestion by mammalian herbivores, further fractionation results in a ~14‰ enrichment between diet and enamel [3]. Thus, herbivores that mainly browse on leaves and other C_3 plants sources have low enamel $\delta^{13}\text{C}$ values (<ca. -8‰), while those that mainly graze on C_4 grasses have high enamel $\delta^{13}\text{C}$ values (>ca. -2‰). Accounting for changes in $\delta^{13}\text{C}$ of atmospheric CO_2 , these end members may be adjusted by about +1.4‰ for the Pliocene [4-6]. Modern tropical grasses using the C_4 photosynthetic pathway favour a warm growing season (summer rainfall) and high temperatures and are more efficient at photosynthesis than C_3 grasses under these conditions [7]. C_4 plants also display a competitive advantage in conditions of low atmospheric CO_2 [8], but all evidence suggests CO_2 levels have been relatively constant at pre-industrial levels since the late Oligocene [9, 10].

Analyzed specimens were collected during surveys conducted by the International Omo Research Expedition [1967-1976, see 11] and by the Omo Group Research Expedition. For age assignment, we used stratigraphic positions recorded at unit (submember) level [12].

Descriptions of sampling methods and analyses of the hippopotamids are presented in Souron et al. [13]. Enamel sampling of both bovid and suid teeth was performed by A.S. at the Authority for Research and Conservation of Cultural Heritage in Addis Ababa. For bovid and suid teeth, tooth surfaces were cleaned with a tungsten abrasive drill bit and enamel was sampled using a

diamond drill bit, each sample of enamel powder weighing around 20 mg. For the suid specimens, treatment and stable isotopic analysis was performed at the University of Tübingen, Germany (Institut für Geowissenschaften, Abteilung Geochemie). Enamel powders were first treated with 2.5% NaOCl for 20 hours to remove organic matter, and rinsed twice with distilled water. They were then reacted with 1M buffer acetic acid-calcium acetate for 24 hours at 20°C to remove diagenetic carbonates, and again rinsed three times with distilled water. They were finally oven-dried for 24 hours at 70°C. Treated bioapatite powders (weighting around 3 mg) were reacted with 100% anhydrous orthophosphoric acid (H₃PO₄) at 70°C for 90 minutes. The resulting CO₂ was analysed using a continuous flow system, a ThermoFisher Scientific GasBenchII, coupled to a Finnigan MAT 252 isotopic ratio mass spectrometer (IRMS).

For the bovid specimens, treatment and stable isotopic analyses was performed at the Stable Isotope Ratio Facility for Environmental Research (SIRFER) at the University of Utah. Enamel powders were treated for 30 minutes with 0.1 M buffered acetic acid, rinsed three times with Milli-Q distilled de-ionized water, and dried overnight at 70°C. Treated bioapatite powders (0.4 to 0.6 mg) were reacted with anhydrous H₃PO₄ at 90°C for 15 minutes using a Finnigan CarboFlo® device coupled to the dual-inlet of a Finnigan MAT 252 IRMS. CO₂ yields from bovid samples show there was no contribution from exogenous carbonate. An acid fractionation factor of 1.00725 is used to convert sample CO₂ back to enamel carbonate δ¹⁸O values [14].

Stable carbon and oxygen isotope ratios are reported as δ values relative to the Pee Dee Belemnite (PDB) standard using permil (‰) notation where $\delta^{13}\text{C} = (\text{R}_{\text{sample}}/\text{R}_{\text{standard}} - 1) \times 1000$, and R_{sample} and $\text{R}_{\text{standard}}$ are the ¹³C/¹²C ratios (or ¹⁸O/¹⁶O ratios in the case δ¹⁸O) in the sample and in the standard, respectively, and the δ¹³C (or δ¹⁸O) value of PDB is defined as 0‰. Results of stable carbon isotopic analyses were corrected using the international standard NBS-19 and analytical precision is ~0.1 ‰ for both δ¹³C and δ¹⁸O in both laboratories. Statistical tests were performed in SAS JMP 10.0, with significance set at p<0.05.

Results

Shapiro-Wilk tests indicate that some of the data distributions differ significantly from normal ($p < 0.05$), so non-parametric tests of significance were used (paired Wilcoxon). The seven bovid teeth from levels B-0, B-2, and B-10 (≥ 2.97 Ma, $\bar{x} = -8.6$ ‰) are significantly depleted in $\delta^{13}\text{C}$ compared to those from levels C-8 to C-9 and G-4 to G-13 ($\leq \sim 2.6$ Ma, $\bar{x} = -4.0$ ‰) (Wilcoxon, $p < 0.001$). The single bovid tooth from B-12 (~ 2.9 Ma) has an intermediate $\delta^{13}\text{C}$ value (-5.1 ‰) and cannot be significantly differentiated from either the pooled older or younger samples (Wilcoxon, $p > 0.15$).

$\delta^{13}\text{C}$ values for the two suid teeth from level B-10 and that from B-12 (≥ 2.850 Ma, $\bar{x} = -6.4$ ‰) show no overlap with those from levels C-4 and younger (≤ 2.740 Ma, $\bar{x} = -0.9$ ‰) (Wilcoxon, $p < 0.01$). Suid teeth from units C-4 to F-0 show slight progressive increases in $\delta^{13}\text{C}$ (ca. 0.5 ‰ mean increases from C-4/C-5 to F-0), with units C-4/C-5 and C-8/C-9 significantly different from unit F0 (Wilcoxon, $p < 0.01$). $\delta^{13}\text{C}$ values from units G-8 and L-9 are also significantly enriched relative to those from units C-4/C-5 (Wilcoxon, $p < 0.05$).

Results of the serial analyses of two fossil hippo canines show that the average $\delta^{13}\text{C}$ value of the canine from level C-9 (2.580 Ma) is enriched by about 5 ‰ relative to that from level B-9 (3.070-2.951 Ma), with no overlap in the ranges of the serial sample distributions [13].

$\delta^{18}\text{O}$ values, while showing some changes in the means and variances among the different stratigraphic levels (especially in the suids), do not show the type of directional change observed in the $\delta^{13}\text{C}$ data. Furthermore, the direction and magnitude of changes in $\delta^{18}\text{O}$ between successive stratigraphic levels is not correlated among the three herbivorous clades. This implies that individual and clade-specific behaviours, physiologies, and environmentally localised effects are the main determinants of $\delta^{18}\text{O}$ rather than large-scale, extrinsic environmental changes affecting all three herbivores simultaneously. Interestingly, the $\delta^{18}\text{O}$ values from OMO 112/2-10014 are

relatively enriched compared to other eastern African fossil or modern hippopotamids with the exception of some modern Turkana hippos which have enamel $\delta^{18}\text{O}$ values ranging from +2.0 to +2.6 ‰ (n=2 individuals) [15]. This suggests the Omo Member B hippopotamid may have lived some part of its life in an evaporated lake or pond.

Supplementary Discussion: Diet of fossil *Tragelaphus*

The high $\delta^{13}\text{C}$ values recovered for *Tragelaphus nakuae* are unexpected in light of the fact that reported enamel $\delta^{13}\text{C}$ values from living tragelaphins reflect diets almost totally dominated by C_3 vegetation [16-18]. Similarly high $\delta^{13}\text{C}$ values indicative of significant C_4 feeding in tragelaphins come from late Miocene and early Pliocene sites at Gona, Ethiopia [4], the middle to late Pliocene of Laetoli [19], and the middle Pleistocene site of Asbole [20]. Approximating with a simple linear mixing model [13, 21], the most positive $\delta^{13}\text{C}$ values (>-3‰) in these fossil tragelaphins could indicate diets with more than 60% C_4 vegetation. In the Upper Laetolil tragelaphins, dental mesowear indicative of strict browsing combined with enriched enamel $\delta^{13}\text{C}$ values implied the possibility of feeding on C_4 dicots rather than C_4 grasses [19, 22].

The sitatunga (*Tragelaphus spekii*) is an example of a living tragelaphin that inhabits swamps and wetlands and is reported to include significant proportions of grass and aquatic plants in its diet [23, 24], though reported $\delta^{13}\text{C}$ values of its enamel indicate it is a strict browser [16]. Among living deer (Cervidae), chital (*Axis axis*), barasingha (*Cervus duvauceli*), and sambar (*Cervus unicolor*) all subsist largely on grasses [25]. Reported fecal $\delta^{13}\text{C}$ values for the chital indicate wet season C_4 -feeding indistinguishable from values for gaur (*Bos gaurus*) [26]. Like tragelaphins, these deer have relatively low-crowned teeth and simple occlusal enamel configurations, contrasting markedly with the hypsodont teeth with complicated enamel found in grazing bovids in Africa today (Hippotragini, Bovini, Alcelaphini, Reduncini). Plio-Pleistocene fossil tragelaphins such as *T. nakuae* may have engaged in one or a variety of the above scenarios,

subsisting on C₄ dicots, wetland grasses, or engaging in seasonal grazing, selecting fresher and greener wet-season grasses that were less abrasive to their low-crowned teeth. The current inability to rule out C₃ grazing in the lower Omo valley prior to 2.8 Ma (see main text) is an additional factor limiting dietary interpretation of enamel isotopic data.

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Supplementary Table 1. Specimen numbers, stratigraphic provenience, $\delta^{13}\text{C}$, and $\delta^{18}\text{O}$ for all bovid and suid samples, and mean values for serial samples of the two hippopotamid specimens reported by Souron et al. [13].

Sample number	Specimen number	Taxon	Tooth Position	Stratigraphic Unit	$\delta^{13}\text{C}$ corrected CaCO_3 vs. PDB	$\delta^{18}\text{O}$ corrected CaCO_3 vs. PDB
BO-OM-03	OMO 20/2-10003	<i>Tragelaphus rastafari</i>	Lm3	B-0	-9.2	0.4
BO-OM-06	W- 99	<i>Tragelaphus rastafari</i>	R m3	B-2	-8.9	-2.7
BO-OM-08	B- 163 b	<i>Tragelaphus rastafari</i>	R m3	B-2	-8.6	-1.1
BO-OM-07	B- 116	<i>Tragelaphus rastafari</i>	R m3	B-2	-8.0	-1.1
BO-OM-01	OMO 28-1970-1853	<i>Tragelaphus rastafari</i>	L M3	B-10	-9.8	0.9
BO-OM-05	L 745-1 (=P610?)	<i>Tragelaphus rastafari</i>	R M3	B-10	-9.4	-3.4
BO-OM-02	OMO 28-1968-2463	<i>Tragelaphus rastafari</i>	L m3	B-10	-6.6	-0.8
BO-OM-04	OMO 3/0-10030	<i>Tragelaphus rastafari/nakuuae</i>	L M3	B-12	-5.1	-1.9
BO-OM-13	OMO P 791/S-1970-2985	<i>Tragelaphus nakuuae</i>	L M3	C-8	-4.8	-2.8
BO-OM-14	OMO 18-1968-2892	<i>Tragelaphus nakuuae</i>	L M3	C-8	-2.8	-3.2
BO-OM-15	OMO 239-1973-4503	<i>Tragelaphus nakuuae</i>	L m3	C-8	-2.7	-2.8
BO-OM-11	L 47-63	<i>Tragelaphus nakuuae</i>	L m3	C-8	-2.7	-1.7
BO-OM-16	OMO 18/sup-10035	<i>Tragelaphus nakuuae</i>	L M3	C-8/C-9	-4.5	-4.8
BO-OM-16	OMO 18/sup-10035	<i>Tragelaphus nakuuae</i>	L M3	C-8/C-9	-4.5	-4.0
BO-OM-12	L 444-1	<i>Tragelaphus nakuuae</i>	L m3	C-9	-5.6	-0.3
BO-OM-10	L 218-2	<i>Tragelaphus nakuuae</i>	L m3	C-9	-4.5	-3.5
BO-OM-09	L 572-1f	<i>Tragelaphus nakuuae</i>	R m3	C-9	-3.1	-3.1
BO-OM-17	L 35-40 e	<i>Tragelaphus nakuuae</i>	L M3	G-4/G-5	-5.5	-1.0
BO-OM-22	OMO 245-1973-4932	<i>Tragelaphus nakuuae</i>	L M3	G-6/G-8	-2.8	-2.3
BO-OM-18	OMO 222-1973-2755	<i>Tragelaphus nakuuae</i>	R m3	G-7	-5.1	0.7
BO-OM-20	OMO 241-1973-4725E	<i>Tragelaphus nakuuae</i>	L m3	G-11	-6.9	-0.9
BO-OM-19	OMO 254-1973-5217	<i>Tragelaphus nakuuae</i>	R M3	G-12-/G13	-2.8	-3.3
BO-OM-21	OMO 249-1973-5028	<i>Tragelaphus nakuuae</i>	L m3	G-13	-3.4	-1.9
BO-OM-23	OMO 257-1973-5341	<i>Tragelaphus nakuuae</i>	L M3	G-13	-2.4	-3.9
SU-OM-01	OMO 211-10012	<i>Kolpochoerus limnetes</i>	L M3	B-10	-8.1	-5.9
SU-OM-02	OMO 112/1-10002	<i>Kolpochoerus limnetes</i>	L m3	B-10	-5.2	-4.4
SU-OM-60	L 367-2	<i>Kolpochoerus limnetes</i>	R M2	B-12	-6.0	-2.2
SU-OM-03	OMO 56-10017	<i>Kolpochoerus limnetes</i>	R M2	C-4/C-5	-2.5	-2.7
SU-OM-04	L 335-27	<i>Kolpochoerus limnetes</i>	R M3	C-4/C-5	-1.0	-4.1
SU-OM-05	L 27-50	<i>Kolpochoerus limnetes</i>	L m3	C-4/C-5	-0.6	-7.7
SU-OM-06	OMO 349-10014	<i>Kolpochoerus limnetes</i>	R M3	C-4/C-5	-3.1	-3.9
SU-OM-07	OMO 56-10015	<i>Kolpochoerus limnetes</i>	L m3	C-4/C-5	-1.2	-3.0
SU-OM-08	OMO 56-10021	<i>Kolpochoerus limnetes</i>	L M2	C-4/C-5	-2.8	-2.4
SU-OM-09	L 193-9 e	<i>Kolpochoerus limnetes</i>	L M3	C-8/C-9	-2.0	-5.1
SU-OM-10	OMO 18-1968-2105	<i>Kolpochoerus limnetes</i>	R M2	C-8/C-9	-2.2	-5.6
SU-OM-11	OMO 84-1976-20	<i>Kolpochoerus limnetes</i>	L M2	C-8/C-9	-2.0	-6.1
SU-OM-12	OMO 18-1968-2103	<i>Kolpochoerus limnetes</i>	R m2	C-8/C-9	-1.5	-5.3
SU-OM-13	OMO 18-1971-2823	<i>Kolpochoerus limnetes</i>	L m2	C-8/C-9	-2.0	-4.9
SU-OM-14	OMO 122-10030	<i>Kolpochoerus limnetes</i>	L m3	C-8/C-9	-0.6	-6.3
SU-OM-15	L 144-16 a	<i>Kolpochoerus limnetes</i>	L M2	C-8/C-9	-0.2	-4.3
SU-OM-16	L 271-10001	<i>Kolpochoerus limnetes</i>	R m3	E-1	-1.2	-4.5
SU-OM-17	OMO 71-1969-219	<i>Kolpochoerus limnetes</i>	L M3	E-1	-3.3	-5.9
SU-OM-18	OMO 166-1973-778	<i>Kolpochoerus limnetes</i>	L M2	E-1	-0.5	-5.8
SU-OM-19	OMO 71-1969-213	<i>Kolpochoerus limnetes</i>	L m3	E-1	-0.1	-4.0

Ecological Change in the Lower Omo Valley: Supplementary Material

Sample number	Specimen number	Taxon	Tooth Position	Stratigraphic Unit	d ¹³ C corrected CaCO ₃ vs. PDB	d ¹⁸ O corrected CaCO ₃ vs. PDB
SU-OM-20	OMO 71-1969-335	<i>Kolpochoerus limnetes</i>	R M3	E-1	-0.2	-3.7
SU-OM-21	OMO 71-1969-214	<i>Kolpochoerus limnetes</i>	L m3	E-1	-1.1	-5.5
SU-OM-22	OMO 71-1969-216	<i>Kolpochoerus limnetes</i>	L m3	E-1	-0.2	-2.8
SU-OM-23	OMO 71-1969-218	<i>Kolpochoerus limnetes</i>	R m3	E-1	-1.3	-5.2
SU-OM-24	OMO 71-1969-215	<i>Kolpochoerus limnetes</i>	L m3	E-1	-0.6	-4.5
SU-OM-25	OMO 71-1969-217	<i>Kolpochoerus limnetes</i>	L m3	E-1	-0.3	-4.2
SU-OM-26	OMO 33-1969-329	<i>Kolpochoerus limnetes</i>	R M3	F-0	0.0	-3.6
SU-OM-27	L 747-4	<i>Kolpochoerus limnetes</i>	L M3	F-0	-1.3	-3.6
SU-OM-28	OMO 33-1969-326	<i>Kolpochoerus limnetes</i>	L m3	F-0	1.1	-0.5
SU-OM-29	OMO 33-1970-2915	<i>Kolpochoerus limnetes</i>	L M3	F-0	0.4	-4.1
SU-OM-30	L 398-2260	<i>Kolpochoerus limnetes</i>	L M2	F-0	-0.9	-3.5
SU-OM-31	L 398-1224	<i>Kolpochoerus limnetes</i>	R m3	F-0	0.0	-1.7
SU-OM-32	OMO 33-1974-6603	<i>Kolpochoerus limnetes</i>	R m2	F-0	0.1	-1.9
SU-OM-33	L 398-2018	<i>Kolpochoerus limnetes</i>	R M3	F-0	-0.5	-3.9
SU-OM-34	L 398-1970	<i>Kolpochoerus limnetes</i>	R m3	F-0	-0.6	-0.5
SU-OM-35	OMO 33/J3-1973-3356	<i>Kolpochoerus limnetes</i>	R M3	F-0	-0.3	-2.3
SU-OM-36	OMO 310-10029	<i>Kolpochoerus limnetes</i>	L M2	G-8	-2.6	-6.5
SU-OM-37	OMO 47-1970-2167	<i>Kolpochoerus limnetes</i>	R M2	G-8	-2.0	-2.5
SU-OM-38	OMO 47-1970-2059	<i>Kolpochoerus limnetes</i>	R M2	G-8	-0.8	-2.5
SU-OM-39	OMO 47-1968-3542	<i>Kolpochoerus limnetes</i>	R M2	G-8	-0.3	-2.6
SU-OM-40	OMO 75/Sd-1970-405	<i>Kolpochoerus limnetes</i>	L M2	G-8	-0.0	-5.6
SU-OM-41	OMO 47-1970-1578	<i>Kolpochoerus limnetes</i>	L M2	G-8	-4.2	-7.4
SU-OM-42	OMO 47-1968-2127	<i>Kolpochoerus limnetes</i>	L M2	G-8	-0.1	-2.0
SU-OM-43	OMO 47-1968-3553	<i>Kolpochoerus limnetes</i>	L m2	G-8	-1.6	-3.4
SU-OM-44	OMO 323-1976-943	<i>Kolpochoerus limnetes</i>	L M2	G-8	-0.3	-4.4
SU-OM-45	OMO 47-1973-1486	<i>Kolpochoerus limnetes</i>	R M3	G-8	0.0	-3.2
SU-OM-46	OMO 323-10008	<i>Kolpochoerus limnetes</i>	L m3	G-8	-0.2	-4.9
SU-OM-47	OMO 323-10034	<i>Kolpochoerus limnetes</i>	L M3	G-8	-0.6	-5.1
SU-OM-48	OMO 323-10013	<i>Kolpochoerus limnetes</i>	L m2	G-8	-0.3	-6.8
SU-OM-49	OMO 310-1976-537	<i>Kolpochoerus limnetes</i>	R m3	G-8	-0.4	-6.6
SU-OM-50	OMO 323-1976-923	<i>Kolpochoerus limnetes</i>	R m3	G-8	-0.5	-6.4
SU-OM-51	OMO 47-1968-2123	<i>Kolpochoerus limnetes</i>	R M3	G-8	-0.4	-1.7
SU-OM-52	OMO K 7-1969-322	<i>Kolpochoerus olduvaiensis</i>	L m3	L-9	-1.1	-3.9
SU-OM-53	OMO K 7-1969-4436	<i>Kolpochoerus olduvaiensis</i>	L M3	L-9	-0.3	-5.5
SU-OM-54	OMO K 7-1969-4430	<i>Kolpochoerus olduvaiensis</i>	m3	L-9	0.5	-0.9
SU-OM-55	OMO 342-10071	<i>Kolpochoerus olduvaiensis</i>	L m3	L-9	-1.7	-3.3
SU-OM-56	OMO 342-10076	<i>Kolpochoerus olduvaiensis</i>	R m3	L-9	-0.1	-2.3
SU-OM-57	OMO 342-10045	<i>Kolpochoerus olduvaiensis</i>	L M2	L-9	-0.4	-2.4
SU-OM-58	OMO 342-10134	<i>Kolpochoerus olduvaiensis</i>	R m3	L-9	-0.3	-2.0
SU-OM-59	OMO 342-10088	<i>Kolpochoerus olduvaiensis</i>	L m3	L-9	0.6	-2.1
mean	OMO 112/2-10014	aff. <i>Hippopotamus protamphibius</i>	lower canine	B-9	-7.3	0.4
mean	OMO 331-10003	aff. <i>Hippopotamus protamphibius</i>	lower canine	C-9	-2.3	-5.5