

Stable isotope-based diet reconstructions of Turkana Basin hominins

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Hominin fossil evidence in the Turkana Basin in Kenya from ca. 4.1 to 1.4 Ma samples two archaic early hominin genera and records some of the early evolutionary history of *Paranthropus* and *Homo*. Stable carbon isotopes in fossil tooth enamel are used to estimate the fraction of diet derived from C₃ or C₄ resources in these hominin taxa. The earliest hominin species in the Turkana Basin, *Australopithecus anamensis*, derived nearly all of its diet from C₃ resources. Subsequently, by ca. 3.3 Ma, the later *Kenyanthropus platyops* had a very wide dietary range—from virtually a purely C₃ resource-based diet to one dominated by C₄ resources. By ca. 2 Ma, hominins in the Turkana Basin had split into two distinct groups: specimens attributable to the genus *Homo* provide evidence for a diet with a ca. 35/65 ratio of C₃- to C₄-based resources, whereas *P. boisei* had a higher fraction of C₄-based diet (ca. 25/75 ratio). *Homo* sp. increased the fraction of C₄-based resources in the diet through ca. 1.5 Ma, whereas *P. boisei* maintained its high dependency on C₄-derived resources.

Theropithecus | hominid

Many approaches have been used to reconstruct the diet of early hominins. Some of the methods focus on the functional morphology of the masticatory system, others focus on tooth wear (both macroscopic and microscopic), and yet others focus on the physicochemical signatures that an animal's diet leaves within its hard tissues (1, 2). Chemical methods include the use of strontium/calcium and barium/calcium ratios (3, 4), but this study focuses on the analysis of stable isotopes of carbon (5–9).

Modern tropical ecosystems differ from those ecosystems that predate the late Miocene. Tropical grasses were rare until the late Miocene, when they greatly expanded in abundance; therefore, by the latest Miocene and Pliocene, many mammals had changed their diets, and some had become dependent on this relatively new dietary resource (10, 11). The study of this dietary evolution is based on the difference in carbon isotope ratios of plants that use either the C₃ or C₄ photosynthetic pathway (12). Plants using the C₃ pathway have $\delta^{13}\text{C}$ values that range between ca. -24‰ and -32‰ (13); the more positive values are associated with xeric environments, intermediate values are associated with mesic environments, and the most negative values are associated with closed canopy environments (14, 15). Plants using the C₄ pathway have $\delta^{13}\text{C}$ values that range from about -10‰ to -14‰ , with more positive values associated with mesic environments and more negative values associated with more xeric environments (16). In the tropics, C₃ plants are primarily trees, shrubs, and nongrassy herbs and forbs; C₄ plants are primarily grasses and sedges, with some rare dicots. A third photosynthetic pathway, Crassulacean acid metabolism, has $\delta^{13}\text{C}$ values similar to C₄ plants in the tropics; Crassulacean acid metabolism plants are mostly succulents in the African tropics and make up a minor but potentially important dietary resource in some circumstances. Carbon

isotope values of animal tissues (e.g., bioapatite) are enriched in ¹³C compared with the diet; for large herbivorous mammals, bioapatite is enriched ca. 12–14‰ relative to dietary materials (5, 17, 18).

Thus, the $\delta^{13}\text{C}$ of fossil tooth enamel can distinguish between diets that are predominantly based on C₃ resources (leaves and fruits from trees and shrubs along with nongrassy forbs and herbs and their fruits) and diets that are predominantly based on C₄ resources (primarily grasses or sedges). Meat and most other organic tissues are only slightly enriched in ¹³C compared with the plant-derived diet (19). Stable carbon isotopes in tooth enamel are unable to distinguish between plant- and meat-based (or insect-based) diet, but they can be used to trace the diet back to the ultimate resource: C₃ or C₄ plants.

The Turkana Basin has an excellent, well-dated record (20–23) of hominin fossils from ca. 4 Ma to the present. Thus, the diets of the hominin taxa represented at sites within the Turkana Basin (Fig. 1) can be used to study dietary preferences within the hominin clade across this time interval. All samples come from collections held at the National Museums of Kenya in Nairobi. We analyzed 110 teeth from 94 different individual hominins for their stable carbon isotopes. For practical reasons, we could not always sample specimens with unambiguous taxonomic assignments, and in some cases, we could sample only associated material. Therefore, we discuss the results in the context of generic rather than specific taxonomic attributions. The genera that we discuss include *Australopithecus* (ca. 4 Ma), *Kenyanthropus* (ca. 3–3.6 Ma), *Paranthropus* (ca. 2.5–1.4 Ma), and *Homo* (ca. 2.3–0.01 Ma). We use the taxonomy favored by Wood (24) and Wood and Leakey (25), although we make no distinction among earlier *Homo* species (e.g., *H. habilis* and *H. rudolfensis*) because of the limitations of the size and quality of the sample. We then compare the results of our analysis of hominins from sites in the Turkana Basin with data from hominins recovered at other locations in eastern and southern Africa.

Results

In this section, we present the results of the stable isotope analyses. We group the Turkana Basin hominin specimens by their geological age (Fig. 2 and Table S1) and discuss the taxa represented in each of the major age groupings.

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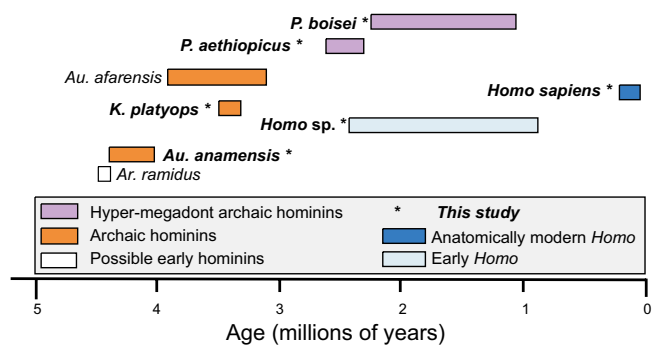


Fig. 1. Age distribution of hominins from East Africa. Isotopic values of lineages in bold are reported in the text.

Intra-individual Variation. For 10 individuals, stable isotope ratios were measured on two to five postcanine teeth. Comparison of the results (Table S1) shows that these individuals have a narrow range of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values among the teeth sampled, with average ranges of 1.0‰ and 0.7‰, respectively. Such a narrow range indicates that these individuals had a fairly homogeneous diet in terms of C_3 - vs. C_4 -derived resources across the time period represented by the development of the teeth sampled for each of the 10 individuals (i.e., based on timescales appropriate to isotope attenuation during enamel maturation). Comparison with other large mammals suggests that molar enamel in early hominins has an isotope maturation interval on the order of 1 or 2 y. Tooth enamel maturation involves an initial stage of bioapatite formation followed by a long period, the isotope maturation interval, wherein the enamel continues to increase in density and incorporate stable isotopes into the bioapatite structure (26). Therefore, the $\delta^{13}\text{C}$ values of individual teeth, as discussed below, seem to provide a reliable but time-integrated signal reflecting the diet of each of the individuals analyzed.

Temporal Samples. 4.2–4.0 Ma. Fossil evidence of *Au. anamensis* is found in ca. 4.0- to 4.2-Ma-old strata in the Turkana Basin; 17 teeth from 12 different individuals were analyzed (Table S1). *Au. anamensis* has a relatively narrow range of $\delta^{13}\text{C}$ values, indicating a diet that is C_3 -based. The average $\delta^{13}\text{C}$ value of $-10.7 \pm 0.8\text{‰}$

corresponds to a $\delta^{13}\text{C}$ diet value of about -25‰ based on an estimated isotopic enrichment (diet bioapatite) for primates of 14‰ (Methods). Such a $\delta^{13}\text{C}$ value is compatible with either a 100% C_3 diet in a mesic to xeric environment or a diet that has both C_3 - and C_4 -derived foods but with the latter making up only ca. 10% of the diet. For comparison, modern browsers (*Giraffa camelopardalis*) (9) from the semiarid region of Tsavo, Kenya, have $\delta^{13}\text{C}_{1750}$ values of $-11.2 \pm 1.1\text{‰}$ ($\delta^{13}\text{C}_{1750}$ refers to isotope values corrected for the anthropogenic addition of ^{13}C -depleted CO_2 to Earth's atmosphere) (Methods), whereas gorillas (*Gorilla beringei*) from densely forested environments in eastern Democratic Republic of Congo have $\delta^{13}\text{C}_{1750}$ values of $-13.5 \pm 1.2\text{‰}$ ($n = 1$) (Table S1). Tooth enamel from modern baboons (*Papio*) from Kenya and Ethiopia has $\delta^{13}\text{C}_{1750}$ values that average $-9.1 \pm 3.1\text{‰}$ ($n = 19$) and range from ca. -13‰ to ca. -2‰ ; baboons from forested regions in Democratic Republic of Congo have $\delta^{13}\text{C}_{1750}$ values that average $-12.2 \pm 2.3\text{‰}$ ($n = 5$) (Methods and Table S1).

Thus, the $\delta^{13}\text{C}$ results for *Au. anamensis* suggest either a C_3 -dominated diet or a diet with a small C_4 component. Published $\delta^{13}\text{C}$ values for *Ardipithecus ramidus* are similar: $-10.2 \pm 1.0\text{‰}$ ($n = 5$) (27). Intertaxon comparison using ANOVA shows that the diets of *Au. anamensis*, *Ar. ramidus*, and modern *G. camelopardalis* (Tsavo) are indistinguishable in $\delta^{13}\text{C}$ space, but the diets of all three taxa are significantly different ($P < 0.0001$) from *G. beringei* from forested habitats (Fig. S1 and Table S1). As is seen below, the diet of *Au. anamensis* differs from the diet of all later hominins from the Turkana Basin.

3.4–3.0 Ma. *K. platyops* is found in the Turkana Basin between ca. 3.0 and 3.4 Ma (28). The only hominin recovered from deposits of similar age in the Awash region of Ethiopia is *Au. afarensis* (29); 21 teeth from 18 different individuals assigned to *K. platyops* were analyzed. The observed range in $\delta^{13}\text{C}$ of this sample (average = -6.2 ± 2.7 , $n = 20$; maximum = -2.7 , minimum = -11.1) is broader than any other hominin included in this study. The only other hominins with such a large range of values are *Au. afarensis* (average = -7.5 ± 2.6 , $n = 20$; maximum = -2.9 , minimum = -13.0) (30) and *Au. africanus* (average = -6.5 ± 2.3 , $n = 23$; maximum = -1.8 , minimum = -11.3) (data in refs. 6, 8, and 31). Compared with modern taxa with a similar sample size, the range and SD for *K. platyops* is broad and large, respectively (14, 32). The $\delta^{13}\text{C}$ values for the 18 *K. platyops* individuals are normally distributed,

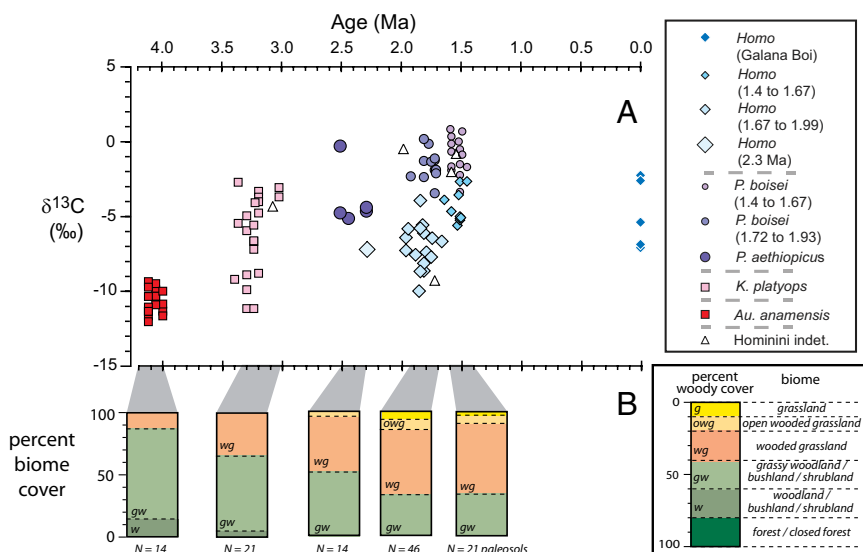


Fig. 2. (A) $\delta^{13}\text{C}$ values of tooth enamel with respect to age for major hominin groups in the Turkana Basin, Kenya. (B) Relative proportions of biomes based on $\delta^{13}\text{C}$ from paleosols (52), where the boundaries between biome types are as described in the text.

and the Akaike Information Criterion (33, 34) does not support a bimodal distribution for this population.

One hominin individual (KNM-ER 5431 F) in this time range is assigned to Homininae indet. It is of about the same age as the *K. platyops* samples discussed above, and its $\delta^{13}\text{C}$ value (-4.3‰) is within the range of *K. platyops*.

Modern *Papio* in East Africa has a similarly wide range of $\delta^{13}\text{C}_{1750}$ values; *Papio* from the Laikipia region of Kenya have values similar to the higher observed values.

2.5–2.3 Ma. Six teeth from five individual hominins in this time range were analyzed in this study. Four individuals attributed to *P. aethiopicus* had $\delta^{13}\text{C}$ values ranging between -0.3‰ and -5.1‰ . Three of these individuals (KNM-WT 16005, KNM-WT 38351, and KNM-WT 38353) have a very narrow range of $\delta^{13}\text{C}$ values—from -4.4‰ to -5.1‰ . The fourth individual attributed to *P. aethiopicus*, KNM-WT 17000, is an outlier compared with the other three *Paranthropus* of this age range. Taken together, *P. aethiopicus* has a diet with a consistently high C_4 component (ca. 50% or greater) in this time interval.

One specimen has been assigned to *Homo* sp. indet. (KNM-WT 42718) (35), and it gave a $\delta^{13}\text{C}$ value of -7.2‰ , which is outside the range of the *P. aethiopicus* specimens of the same age, although the sample size of *P. aethiopicus* from this time interval ($n = 4$ individuals) is small.

1.99–1.67 Ma. The sample from this temporal interval includes two morphologically distinctive hominin taxa, *P. boisei* and *Homo* sp. indet.; 13 teeth from 13 different individual *P. boisei* specimens have an average $\delta^{13}\text{C}$ value of $-1.6 \pm 1.0\text{‰}$ ranging from 0.2‰ to -3.4‰ . These values represent a diet dominated by C_4 resources (i.e., a C_3/C_4 -based resources ratio of ca. 25/75). The 16 *Homo* sp. indet. specimens have $\delta^{13}\text{C}$ values significantly different ($P < 0.001$, ANOVA, Tukey posthoc) from the *P. boisei* individuals in the same age range ($-7.0 \pm 1.5\text{‰}$, $n = 16$; i.e., a C_3/C_4 -based resources ratio of ca. 65/35).

Two specimens in this time interval have proven difficult to classify. One of these specimens, KNM-ER 1482 (a taxonomically enigmatic mandible) (24, 36, 37), has a $\delta^{13}\text{C}$ value of -0.4‰ . The other, KNM-ER 2607 (a taxonomically enigmatic lower molar fragment) (24, 36, 38), has a $\delta^{13}\text{C}$ value of -9.2‰ .

1.65–1.45 Ma. Both *P. boisei* and *Homo* sp. indet. are represented among the specimens from this time interval. The *P. boisei* individuals ($n = 14$) have an average $\delta^{13}\text{C}$ value ($-0.9 \pm 1.2\text{‰}$) that does not differ statistically from the *P. boisei* individuals in the 1.99–1.67 Ma time range. The $-0.9 \pm 1.2\text{‰}$ value corresponds to a C_3/C_4 -based resources ratio of ca. 20/80.

Ten *Homo* sp. indet. specimens in this age range have an average $\delta^{13}\text{C}$ value of $-4.3 \pm 1.1\text{‰}$ (i.e., a C_3/C_4 -based resource ratio of ca. 45/55). The *Homo* sp. indet. individuals in this age range differ significantly from the coeval *P. boisei* sample (ANOVA, Tukey posthoc test, $P < 0.001$), and they also differ from *Homo* sp. indet. individuals from the earlier (1.99–1.67 Ma) time range in that there is a ca. 20% increase in the C_4 diet component (ANOVA, Tukey posthoc test, $P < 0.001$).

Two specimens that cannot be easily assigned to either *Homo* sp. indet. or *Paranthropus*, KNM-ER 2593 and KNM-ER 42705, were both found in the Area 6/6A region near Ileret, where many *P. boisei* specimens have been recovered. They have $\delta^{13}\text{C}$ values similar to the values of *Paranthropus* from Area 6/6A and may well be attributable to this genus.

0.01 Ma. Five teeth from four individual hominins from the Galana Boi Formation (Holocene) have an average $\delta^{13}\text{C}$ value of $-4.8 \pm 2.3\text{‰}$ (i.e., a C_3/C_4 -based resources ratio of ca. 50/50). These values are not significantly different from the earlier *Homo* sp. indet. samples.

Oxygen isotopes. The range of variation of the stable oxygen isotopes ($\delta^{18}\text{O}$) among the groups discussed above is between 0.7‰ and -1.8‰ (the individual range is from ca. $+4\text{‰}$ to -4‰); SDs within each group are ca. $\pm 1.5\text{‰}$. These values and ranges of

variation are equivalent to water-dependent species such as suids and elephantids (39) as well as carnivores and omnivores. $\delta^{18}\text{O}$ as a function of time comparing the different hominins is shown in Fig. S2.

Discussion

Diets of Early Hominins: C_3 - and C_4 -Based Resources. We use the terms C_3 - and C_4 -based resources throughout our discussion, because our isotopic method cannot distinguish between a plant-based diet, a meat-based diet, and an omnivorous diet. Thus, based on isotopes alone, we consider that the diets of the early hominins that we have investigated could be primarily herbaceous (C_3 and C_4 plants), or they could be a secondary C_3 - or C_4 -based diet, an apparent C_3 - or C_4 -based diet, or an omnivorous diet. A secondary C_3 - or C_4 -based diet could be a meat- or insect-based diet (in which the $\delta^{13}\text{C}$ values are derived from the basal herbaceous diet of the prey). An apparent C_4 -based diet is one based on aquatic resources in which algae have elevated $\delta^{13}\text{C}$ values because of bicarbonate uptake during photosynthesis (40); for this example, algae or fish then have $\delta^{13}\text{C}$ values with an apparent C_4 component (41, 42). Lastly, an omnivorous diet is a combination of the above resources: primary herbaceous diet along with secondary C_3 - or C_4 -derived components (i.e., meat or insects) or apparent components (i.e., aquatic).

The stable carbon isotope signature of a meat-based diet depends on the nature of the prey: small bovid herbivores less than ca. 10 kg (e.g., dik-dik and other neotragines) tend to be browsers and have C_3 -based diets (14, 32), whereas large herbivores can have diets that are C_3 -based (browsers such as most tragelaphines, black rhinos, and giraffes), C_4 -based (grazers such as warthogs, zebra, alcelaphines, redecines, and bovines), or mixed (e.g., impala, and some gazelles). Thus, the size of prey may be important in considering possible secondary diet C_3 or C_4 resources. Other small mammals (e.g., hyrax, lagomorphs, or rodents) could have been an important dietary resource and would contribute to isotope mixing lines between C_3 - and C_4 -based end member values.

Evolution of Hominin Diets Between 4 and 1.4 Ma in Eastern Africa.

The earliest hominin taxon sampled in this study, the ca. 4 Ma *Au. anamensis*, has a diet comprised primarily of C_3 -based resources (an average ca. 90/10 ratio of C_3/C_4 diet resources with a range from 100/0 to 80/20 for C_3/C_4 -based resources). This finding is not entirely unexpected, because the diets of the obvious outgroups for hominins, *Pan* and *Gorilla*, are both predominantly C_3 -based (43–45). It is impossible to refute the hypothesis that some C_4 resources contributed to the diet of these *Au. anamensis* individuals, and we do not attempt to do so. The observed $\delta^{13}\text{C}$ range of *Au. anamensis* is narrow, and it is similar to the slightly older *Ar. ramidus* found in the Awash region of Ethiopia (27). A diet with this carbon stable isotope signature is likely dominated by plant foods. The only alternative is a diet based on meat/insect resources based on animals that themselves consume almost entirely C_3 resources. However, note that initial surveys of fossil mammals from the Turkana region show that, by 7 Ma and on, most herbivores in the Turkana Basin had C_4 -based diets (10, 11, 46, 47). Thus, *Au. anamensis* would have to have been a very specialized hunter if meat were a significant portion of the diet, because the prey would have to have been exclusively C_3 consumers.

By 3.5 Ma, the diet of the hominins that we sampled had expanded to include significant C_4 resources. The diet of *K. platyops* shows a broad range, with some individuals having strongly C_3 -based diets and others having C_4 -dominated diets. The range of values for 18 *K. platyops* individuals corresponds to $\delta^{13}\text{C}$ diet average values of ca. -25‰ to -17‰ ; the average *K. platyops* diet corresponds to a C_3/C_4 -based resources ratio of ca. 60/40, but the range of the C_3/C_4 -based resources ratio, 95/5 to 35/65, is wide. This wide range of dietary C_3 vs. C_4 resources suggests that *K. platyops* expanded into a dietary niche hitherto unexploited by

hominins in the Turkana Basin. $\delta^{13}\text{C}$ values of *Au. afarensis* (30), another hominin taxon in East Africa of similar age, and *Au. africanus* in southern Africa of less certain age (6, 8, 31) similarly have a wide range of $\delta^{13}\text{C}$ values. The work by Sponheimer et al. (48) discusses these similarities and differences in more detail.

One individual in the small sample of *P. aethiopicus*, the KNM-WT 17000 cranium (49), deserves special comment. Its left M2 has a $\delta^{13}\text{C}$ value of -0.3‰ , indicating a C_4 -dominated diet (ca. 15/85 for the C_3/C_4 diet ratio), which is a diet similar to the *P. boisei* sample in the later time range. The dietary breadth within *Paranthropus* by ca. 2.3 Ma needs to be investigated with additional samples and analyses.

Between 2.0 and 1.4 Ma, numerous *P. boisei* and *Homo* sp. indet. specimens show that the diets of the two genera were distinct, with *Paranthropus* having a diet comprised of a 20/80 C_3/C_4 diet ratio, whereas *Homo* sp. indet. shows C_3/C_4 -derived ratio values that range from 25/75 to 45/55. Previous comparisons with southern African fossils suggest that *P. boisei* from East Africa had a diet that was much narrower in terms of C_3/C_4 resources than *P. robustus* from southern Africa (9), with a wide range of $\delta^{13}\text{C}$ values that indicates a much broader dietary niche.

The taxonomically enigmatic mandible KNM-ER 1482 (50) has a $\delta^{13}\text{C}$ value of -0.4‰ , which is intriguing. It has shifted even farther in the direction of being dependent on C_4 resources than most *P. boisei*. Its mandibular and dental morphology offers little or no evidence to assign it to *P. boisei*. Indeed, some have suggested that it may belong to the same taxon as the KNM-ER 1470 cranium (50) and the KNM-ER 62000 maxilla (51). If this proves to be the case, then within the same region, there may be at least two hominin taxa, almost certainly in different lineages, that have shifted to a diet dominated by C_4 resources.

Paleoecology of the Koobi Fora and Nachukui Formations. Precessional climatic cycles of ca. 20,000 y duration are widely recognized in marine and lacustrine sequences in tropical latitudes. Between insolation maxima and minima (separated by ca. 10,000 y), there are significant changes in rainfall and ecology. Fluvial strata present challenges for quantitative paleoenvironmental interpretation at timescales less than 20,000 y because of their abrupt and discontinuous mode of deposition. A discrete sedimentary package associated with a particular insolation cycle still does not reveal whether a fossil was deposited at maximum, minimum, or intermediate insolation. Furthermore, matching a fossil with the paleoenvironment in which it lived requires knowing the part of a cycle that a paleoenvironmental indicator (e.g., paleosol carbonate, mineralogy, indicator fossil, or biomarker) records. A vertebrate fossil from the base of a 20,000-y fining upward sequence may have lived during a climatic milieu different from the climate under which carbonate formed in a paleosol at the top of the same sequence. In most situations, it is not feasible to relate a fossil from fluvial sediments to a particular part of a precessional cycle, and it is certainly not possible using legacy collections or surface finds. Nonetheless, long-term ecological changes can be discerned through the 3-Ma record considered here.

Stable isotopes also provide important constraints on the paleoecology of the Turkana Basin. The earliest hominins reported here, from ca. 3 to 4 Ma, lived in an environment that was predominantly ca. 40–60% woody cover, which was determined from paleosol $\delta^{13}\text{C}$ values (52, 53). For this period, the soil carbon contribution from C_3 woody plants, C_3 forbs and herbs, and C_4 grasses would be ca. 60–40%, 15–20%, and 25–40%, respectively (Fig. 2B and Fig. S3). Such a habitat would be a grassy woodland, grassy shrubland, or grassy bushland (54). Sedimentological evidence (55) shows that the proto-Omo river was present throughout this period; this river likely had a riparian forest (>80 woody cover) that may have been hundreds of meters wide; Δ_{47} measurements on paleosols indicate that the region had soil temperatures between 30 °C and 40 °C (56), indicating a regional temperature regime similar

to the temperature regime of today. Thus, this region had a riparian corridor with cooler temperature and little to no C_4 resource availability, but close by, the woodland/shrubland/bushland was a more open habitat with significant C_4 resources and much higher daily temperatures than in the riparian corridor. These paleoecological conditions suggest that, based on dietary considerations, *Au. anamensis* may have been restricted to a narrow riparian corridor, whereas *K. platyops* must have ventured into open habitats to obtain C_4 dietary resources. Thus far, fossils of *K. platyops* are associated with alluvial fans of a large lateral stream on the western basin margin interfingering with deposits of the ancestral Omo River.



Fig. 3. Images of KNM-ER 45502 before and after sampling. (A) Top view of tooth before sampling. (B) View of the tooth with sample powder (1.8 mg) after sampling. (C) Sample before sampling; the box shows the area chosen for sampling (E). (D) Sample after sampling (same view as C); the boxed area is the close-up view shown in F. (E) Close-up view of the area sampled for stable isotope analysis before sampling. The red arrow shows the broken enamel surface to be sampled. (F) The same area as E but after sampling. The red arrow points to the surface sampled.

Woody cover diminished in the region over time; between *ca.* 2.0 and 1.4 Ma, woody cover was 20–40% based on $\delta^{13}\text{C}$ in paleosols (52). Such an ecosystem is equivalent to wooded grassland with soil contributions of C_3 woody plants, C_3 forbs and herbs, and C_4 grasses of *ca.* 40–20%, 20–30%, and 40–50%, respectively (Fig. 2B); areas of true grassland [$<10\%$ woody cover in the United Nations Educational, Scientific, and Cultural Organization terminology (54)] were uncommon, at least on the timescale of paleosol formation ($>1,000$ y). This change represents a great increase in the availability of C_4 plants for *Homo* and *Paranthropus* compared with the earlier *Australopithecus* and *Kenyanthropus* and a significant opening of the landscape. The 2.0- to 1.4-Ma interval had intermittent lakes fed by the proto-Omo River; however, it may have been diverted to the Nile drainage for some periods during this interval (55). Geochemical and mineralogic evidence shows that some of these lakes were alkaline (56); Δ_{47} evidence from paleosols indicates high mean annual temperatures, similar to the temperatures of today (57).

Thus, from 4.1 to 1.4 Ma, the region had abundant C_4 resources available in the 30-km broad grassy woodland/shrubland to wooded grasslands that bordered narrow (hundreds of meters wide) riparian forests or woodlands associated with the proto-Omo River.

Comparison of Hominin Diets to *Theropithecus*. *Theropithecus* was another large-bodied primate in the Turkana Basin at this time. Stable isotope measurements of tooth enamel show that *Theropithecus* was a heavy C_4 consumer by 4 Ma, with *ca.* 65% C_4 resources contributing to the diet (58). Throughout the period from 4 to 1 Ma, *Theropithecus* had a diet that was as much or more C_4 -based than any hominin. *Paranthropus*, from 1.4 to 2.0 Ma, had a diet that was *ca.* 75% C_4 -based, whereas the coeval *Theropithecus* had a diet that was *ca.* 75–85% C_4 -based (58).

Modern Primates as Analogs for Hominin Diets. Modern gorilla and chimpanzees have diets that are entirely or almost entirely C_3 -based (data in Table S2 and refs. 43–45). Only the earliest hominin in this study could be interpreted as having had a C_3 -based diet with minimal (if any) C_4 components; the $\delta^{13}\text{C}$ of *Au. anamensis* is more positive than gorillas or chimpanzees from closed canopy forests, but it is compatible with a pure C_3 diet from riparian forests or open habitats.

Modern baboons (*P. anubis* and *P. hamadryas*) have a wide range of $\delta^{13}\text{C}_{1750}$ values, showing diet strategies that range from essentially pure C_3 -based (e.g., from Neshisar NP) (Table S2) to dominated by C_3 -based resources but with measureable C_4 -based resources (Gona, Ologesailie, Tsavo, and Turkana) (Table S2) to subequal with respect to C_3 - and C_4 -based resources (e.g., Laikipia region) (Table S2). Baboons have been suggested as an important study analog for early hominins (59, 60); thus future studies of baboon diets, coupled with stable isotope analyses, will be a fruitful avenue of research.

Conclusions

Within the past 4 Ma, the earliest dietary isotope evidence from hominins in the Turkana Basin comes from a single species,

Au. anamensis, with a diet dominated by C_3 resources but possibly with a small component of C_4 -derived resources. By *ca.* 3.5 Ma, at least one hominin taxon, *Kenyanthropus*, in the Turkana Basin had a diet with a broad range of C_3/C_4 -based resources. By the 1.99- to 1.67-Ma time period, at least two morphologically highly distinctive hominin taxa, *P. boisei* and *Homo* sp. indet., had shifted in the direction of consuming higher but different proportions of C_4 resources. We cannot determine from the stable isotopes by themselves what the C_4 resources were that caused this shift in diet.

Methods

Hominin teeth from the National Museums of Kenya were sampled using a high-speed rotary drill to obtain powder (*ca.* 2–5 mg) from each sample. Only hominin teeth with broken surfaces were sampled; sampling was from the exposed broken enamel (Fig. 3). Enamel powder from modern gorilla (*G. beringei*) was obtained from archived samples in Kahuzi-Biega National Park and the Centre de Recherche National en Sciences Naturelles (CRNS)-Lwiro, Democratic Republic of Congo; most gorilla samples were young adults that had been killed by poachers. Other modern primates were from Democratic Republic of Congo and Kenya. All samples were treated with 0.1 M buffered acetic acid for 30 min to remove secondary carbonates; we had about 50% recovery during this treatment.

Fossil samples (*ca.* 500 μg) were reacted with 105% phosphoric acid at 90 °C in silver capsules on an isotope ratio mass spectrometer after cryogenic separation of CO_2 at the University of Utah Stable Isotope Ratio Facility for Environmental Research (SIRFER). Modern samples from Democratic Republic of Congo were analyzed in the Archaeology Department at the University of Cape Town using a Kiel device coupled to an isotope ratio mass spectrometer. Results are reported using the standard per million (‰) notation, where

$$\delta^{13}\text{C} = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1,000$$

and R_{sample} and R_{standard} are the $^{13}\text{C}/^{12}\text{C}$ ratios in the sample and standard, respectively (Vienna–Pee Dee Belemnite is the standard for carbon isotope measurements). Corrections for temperature-dependent isotope fractionation in oxygen were made using modern and fossil internal reference materials that had been reacted at 25 °C (61). For comparative purposes, modern mammals have had their $\delta^{13}\text{C}$ values adjusted to compensate for recent changes in atmospheric $\delta^{13}\text{C}$ values (62, 63); these values are referred to in the text as $\delta^{13}\text{C}_{1750}$. We use the year of death to calculate the $\delta^{13}\text{C}_{1750}$ value; this date will result in a maximum correction, because tooth enamel likely formed *ca.* 10 y before death for these individuals.

Age estimates for each hominin use the correlations and chronology of the >350 volcanic ashes in the basin (20–23, 64); taxonomic assignments are in refs. 24 and 25.

SI Methods has additional information on isotope enrichment factors in mammals, stratigraphic information and age estimates for individual hominins (Table S3), statistical treatment, taxonomic assignments, and biome classifications used in this work.

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Supporting Information

Cerling et al. 10.1073/pnas.1222568110

SI Methods

Sampling and Analytical Methods. Hominin teeth were sampled and analyzed as described in *Methods*. Results are presented in Table S1.

Isotope Enrichment Factors for Mammals. In our discussion, we estimate that the isotope enrichment for primates is likely *ca.* 14‰ (1). Thus, a pure C₃ diet would have a tooth enamel value of *ca.* -12‰ in mesic environments (i.e., *ca.* -26‰ for mesic pre-Industrial C₃ plants), whereas a pure C₄ diet would have a δ¹³C value of *ca.* +2‰ to +4‰ (i.e., δ¹³C₁₇₅₀ values of -12‰ to -10‰ for pre-Industrial C₄ plants). These nominal values of -26‰ and -12‰ for C₃ and C₄ plants, respectively, along with an enrichment of 14‰ for diet bioapatite will be used for discussions concerning the fraction of C₃- and C₄-based resources in diets.

Stratigraphic Information and Age Estimates for Hominins. Age ranges for hominins are based on their stratigraphic position relative relationship to the >350 layers of volcanic ash in the basin, of which >40 layers now have precise K-Ar or ⁴⁰Ar/³⁹Ar dates (2–6). These ages are further constrained by paleomagnetic information in some sections (2–6). In most instances, ages of hominins were computed by linear interpolation between stratigraphic levels of known age and the stratigraphic level of the hominin in question, but in some instances, the age was computed by linear extrapolation above or below stratigraphic levels of known age. Stratigraphic markers for individual hominins are given in Table S2.

Statistical Treatment. ANOVA and other statistical analyses were performed using JMP.

Taxonomic Assignments of Hominins. Taxonomic assignments are based on the material analyzed for stable isotope studies. Our sampling strategy has been to analyze only broken enamel surfaces so as not to disturb primary surfaces that might be of use to taxonomists and morphologists. Therefore, in some cases, we analyzed fragmentary material found in association with more complete fossils. Although it has been formerly assumed that this material is derived from the same organism, it is possible that, in some cases, this fragmentary material derives from a different individual and perhaps, even a different taxon. We use the identifications in Wood's (7) monograph on the Koobi Fora hominins and the recent compilation of Omo-Turkana Basin hominins (8) as a starting point. Several samples have had a history of being difficult to assign to a particular taxon, because they do not fit neatly in either *Paranthropus* or *Homo*; five such samples (KNM-ER 1482, 2593, 2607, 5431, and 42705) are assigned to Hominidae indet.

Biome Classification. The discussion of biomes is based on the United Nations Educational, Scientific, and Cultural Organization classification for African vegetation (9), which is primarily based on the fraction of woody cover; we further subdivide that nomenclature to allow better description of the continuum between 0% and 100% woody canopy cover. Woody cover percentages are used to describe biomes: grasslands, 0–10%; open woody grasslands, 10–20%; woody grasslands, 20–40%; grassy woodlands/bushlands/shrublands, 40–60%; woodlands/bushlands/shrublands, 60–80%; forests, 80–100%. These definitions and nomenclature are used to estimate the percentage woody cover in the geological record based on paleosols (10).

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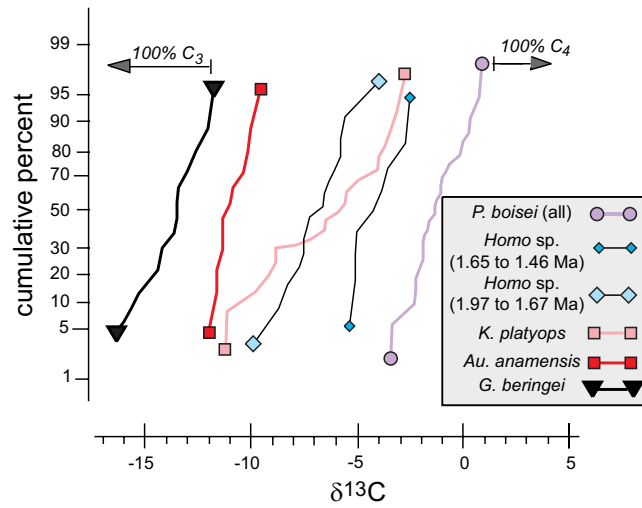


Fig. S1. Cumulative probabilities of $\delta^{13}\text{C}$ values for hominin groups ($n > 5$ individuals) in the Turkana Basin.

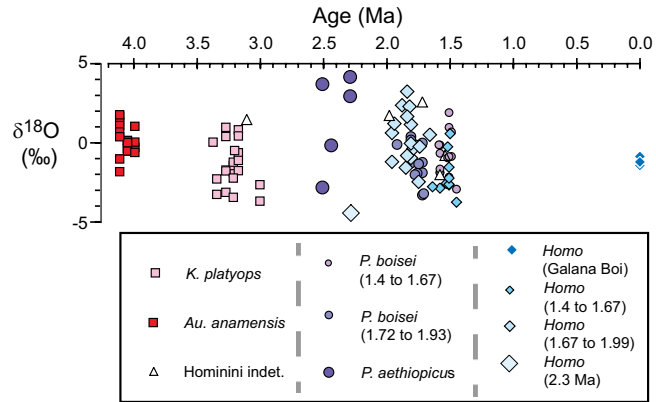


Fig. S2. $\delta^{18}\text{O}$ of hominin teeth as a function of age and taxon for the Turkana Basin. Values are reported in Table S1.

Table S1. Stable isotope values of hominins in this study grouped by age

Specimen no.	Element	Taxon	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	Age (Ma)	\pm (Ma)
4.12–3.95 Ma						
KNM-ER 18540	m frag	<i>Australopithecus anamensis</i>	−11.3	−0.6	4.00	0.05
KNM-ER 20420	lt M2	<i>Au. anamensis</i>	−10.8	−0.1	4.00	0.05
KNM-KP 29287	rt m1	<i>Au. anamensis</i>	−9.9	0.1	4.06	0.04
KNM-KP 29287	rt m2	<i>Au. anamensis</i>	−9.5	−0.5	4.06	0.04
KNM-KP 29287	rt m3	<i>Au. anamensis</i>	−10.3	−0.4	4.06	0.04
KNM-KP 29287	lt m3	<i>Au. anamensis</i>	−10.9	0.4	4.06	0.04
KNM-KP 29287A	lt m2	<i>Au. anamensis</i>	−10.3	0.4	4.06	0.04
KNM-ER 30200B	lt M3	<i>Au. anamensis</i>	−11.6	−0.1	4.00	0.05
KNM-KP 30498D	lt M3	<i>Au. anamensis</i>	−11.6	1.0	4.12	0.04
KNM-KP 30502D	rt m3	<i>Au. anamensis</i>	−9.3	−1.7	4.12	0.04
KNM-KP 30502E	lt m3	<i>Au. anamensis</i>	−9.7	−1.1	4.12	0.04
KNM-ER 30745	lt M3	<i>Au. anamensis</i>	−10.0	1.3	4.00	0.05
KNM-KP 35839	lt P3	<i>Au. anamensis</i>	−11.3	0.3	4.12	0.04
KNM-KP 35840A	lt M3	<i>Au. anamensis</i>	−11.0	1.7	4.12	0.04
KNM-KP 35842	M	<i>Au. anamensis</i>	−10.3	—	4.12	0.04
KNM-KP 35847	lt m2	<i>Au. anamensis</i>	−12.0	1.3	4.12	0.04
KNM-KP 35851	lt M3	<i>Au. anamensis</i>	−11.3	1.1	4.12	0.04
3.4–3.0 Ma						
KNM-WT 8556B	m	<i>Kenyanthropus platyops</i>	−6.6	−3.3	3.24	0.10
KNM-WT 16006	lt m2	<i>K. platyops</i>	−5.4	−3.3	3.37	0.05
KNM-WT 22936	rt m1	<i>K. platyops</i>	−9.2	0.1	3.40	0.20
KNM-LT 23181	rt dM2	<i>K. platyops</i>	−4.9	0.9	3.30	0.20
KNM-LT 23182	rt m3	<i>K. platyops</i>	−5.9	0.5	3.30	0.20
KNM-LT 25936	P frag	<i>K. platyops</i>	−8.9	−1.7	3.30	0.20
KNM-WT 38332	rt M2	<i>K. platyops</i>	−2.7	−2.3	3.37	0.05
KNM-WT 38335	M	<i>K. platyops</i>	−5.6	−3.5	3.24	0.10
KNM-WT 38338	M2	<i>K. platyops</i>	−9.9	−3.3	3.30	0.10
KNM-WT 38342	lt m1	<i>K. platyops</i>	−11.1	−3.2	3.30	0.10
KNM-WT 38344	m1 or m2	<i>K. platyops</i>	−3.7	−3.7	3.03	0.10
KNM-WT 38346	M	<i>K. platyops</i>	−8.8	0.8	3.20	0.10
KNM-WT 38350	lt M	<i>K. platyops</i>	−11.1	−1.2	3.24	0.10
KNM-WT 38356	M1 or M2	<i>K. platyops</i>	−3.0	−2.5	3.03	0.10
KNM-WT 38358B	lt m2	<i>K. platyops</i>	−4.7	−1.6	3.20	0.10
KNM-WT 38358C	lt m3	<i>K. platyops</i>	−3.3	−1.2	3.20	0.10
KNM-WT 38358D	lt m1	<i>K. platyops</i>	−3.7	−0.1	3.20	0.10
KNM-WT 38358F	rt M3	<i>K. platyops</i>	−4.0	−0.3	3.20	0.10
KNM-WT 38359	m1 or m2	<i>K. platyops</i>	−4.0	−0.4	3.23	0.10
KNM-WT 38361H	lt P4	<i>K. platyops</i>	−7.2	−1.7	3.24	0.10
KNM-WT 38362B	lt M1 or M2	<i>K. platyops</i>	−6.6	−2.3	3.24	0.10
KNM-ER 5431F	lt p4	Hominini indet.	−4.3	1.5	3.10	0.10
2.25–2.55 Ma						
KNM-WT 16005	lt m2	<i>Paranthropus aethiopicus</i>	−5.1	−0.2	2.45	0.05
KNM-WT 17000	lt M2	<i>P. aethiopicus</i>	−0.3	−2.7	2.52	0.05
KNM-WT 38351	lt M frag	<i>P. aethiopicus</i>	−4.7	3.8	2.30	0.05
KNM-WT 38353A	m1 or m2	<i>P. aethiopicus</i>	−4.6	4.2	2.30	0.05
KNM-WT 38353B	lt m1 or m2	<i>P. aethiopicus</i>	−4.4	3.0	2.30	0.05
KNM-WT 42718	rt m1	<i>Homo</i> sp.	−7.2	−4.4	2.29	0.03
1.99–1.67 Ma						
KNM-ER 816B	M frag	<i>P. cf boisei</i>	−1.9	−1.3	1.73	0.03
KNM-ER 3952F	lt M3	<i>P. cf boisei</i>	−1.2	0.0	1.82	0.05
KNM-ER 732A	rt P4	<i>P. boisei</i>	−0.1	−1.8	1.78	0.10
KNM-ER 810	p3	<i>P. boisei</i>	−3.4	−3.3	1.73	0.03
KNM-ER 1469A	lt m3	<i>P. boisei</i>	−2.3	−0.1	1.93	0.04
KNM-ER 1479A	m3	<i>P. boisei</i>	−2.3	0.2	1.82	0.05
KNM-ER 1804	lt M3	<i>P. boisei</i>	−1.2	−0.7	1.73	0.03
KNM-ER 1806C	rt m3	<i>P. boisei</i>	−1.3	−2.0	1.76	0.04
KNM-ER 13750	m frag	<i>P. boisei</i>	0.2	0.5	1.82	0.05
KNM-ER 15940	lt m3	<i>P. boisei</i>	−1.1	−0.6	1.73	0.03
KNM-WT 17396	lt m3	<i>P. boisei</i>	−1.9	−3.1	1.77	0.03
KNM-WT 37100	m2 or m3	<i>P. boisei</i>	−1.8	−1.5	1.77	0.03
KNM-WT 37748	rt M3	<i>P. boisei</i>	−2.1	0.0	1.77	0.03
KNM-ER 1478A	m frag	<i>Homo</i> sp.	−8.6	1.3	1.82	0.05

Table S1. Cont.

Specimen no.	Element	Taxon	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	Age (Ma)	\pm (Ma)
KNM-ER 1478A	M2	<i>Homo</i> sp.	-8.1	0.0	1.82	0.05
KNM-ER 1483E	m frag	<i>Homo</i> sp.	-7.5	2.4	1.89	0.03
KNM-ER 1593C	m1	<i>Homo</i> sp.	-7.4	2.1	1.80	0.07
KNM-ER 1802B	lt M3 or m3	<i>Homo</i> sp.	-6.4	-1.2	1.97	0.03
KNM-ER 1805	lt m1	<i>Homo</i> sp.	-7.7	-2.4	1.76	0.04
KNM-ER 1814E	m3	<i>Homo</i> sp.	-6.6	0.6	1.67	0.10
KNM-ER 2599	lt p4	<i>Homo</i> sp.	-9.9	-1.6	1.86	0.03
KNM-ER 2600	m-frag	<i>Homo</i> sp.	-6.1	-1.0	1.82	0.05
KNM-ER 3734	lt m3	<i>Homo</i> sp.	-5.8	1.2	1.95	0.03
KNM-ER 7330	rt P3	<i>Homo</i> sp.	-5.5	2.3	1.83	0.04
KNM-WT 37745	rt p3	<i>Homo</i> sp.	-6.4	-0.2	1.75	0.05
KNM-ER 45501	m frag	<i>Homo</i> sp.	-5.8	-0.7	1.85	0.10
KNM-ER 45502	lt m1 or m2	<i>Homo</i> sp.	-3.9	3.4	1.85	0.10
KNM-ER 45503	M2 or M3	<i>Homo</i> sp.	-8.6	1.7	1.85	0.10
KNM-ER 62000	rt M1	<i>Homo</i> sp.	-7.2	0.6	1.97	0.04
KNM-ER 1482A	lt m2	Hominini indet.	-0.4	1.8	1.99	0.05
KNM-ER 2607	m frag	Hominini indet.	-9.2	2.6	1.73	0.10
1.65–1.46 Ma						
KNM-ER 3887	rt M3	<i>P. cf boisei</i>	-1.7	-2.9	1.46	0.03
KNM-ER 729A	lt p4	<i>P. boisei</i>	0.0	-0.7	1.53	0.03
KNM-ER 733A	rt m3	<i>P. boisei</i>	-1.5	-2.6	1.52	0.03
KNM-ER 733D	lt P4	<i>P. boisei</i>	-0.5	-2.2	1.52	0.03
KNM-ER 801C	lt m3	<i>P. boisei</i>	0.4	-1.8	1.59	0.04
KNM-ER 802D	lt m1	<i>P. boisei</i>	-0.1	-1.7	1.59	0.04
KNM-ER 802G	m3	<i>P. boisei</i>	-1.9	0.0	1.59	0.04
KNM-ER 818	lt m3	<i>P. boisei</i>	0.7	1.9	1.50	0.05
KNM-ER 1171C	lt m1	<i>P. boisei</i>	-0.6	-1.9	1.59	0.04
KNM-ER 1819	m3	<i>P. boisei</i>	0.9	-0.7	1.60	0.10
KNM-ER 3737B	rt m1	<i>P. boisei</i>	-1.6	-2.5	1.59	0.04
KNM-ER 6080	rt m2	<i>P. boisei</i>	-2.2	-0.6	1.52	0.03
KNM-ER 6082	lt p3	<i>P. boisei</i>	-0.8	1.1	1.50	0.04
KNM-ER 15951F	m frag	<i>P. boisei</i>	-3.3	-0.9	1.52	0.03
KNM-ER 730A	lt m1	<i>Homo</i>	-2.6	-0.7	1.54	0.05
KNM-ER 807	lt M1	<i>Homo</i>	-5.6	-1.7	1.52	0.05
KNM-ER 807	lt M2	<i>Homo</i>	-5.2	-2.2	1.52	0.05
KNM-ER 808G	rt M1	<i>Homo</i>	-5.1	-2.2	1.52	0.03
KNM-ER 809A	lt m1	<i>Homo</i>	-5.0	-2.6	1.53	0.03
KNM-ER 820	lt dm2	<i>Homo</i>	-3.5	-0.2	1.51	0.05
KNM-ER 992B	lt c	<i>Homo</i>	-5.0	0.6	1.46	0.03
KNM-ER 1808I	m frag	<i>Homo</i>	-2.6	-3.7	1.59	0.03
KNM-ER 3733	lt M1	<i>Homo</i>	-4.6	-2.8	1.65	0.05
KNM-ER 3733	lt M2	<i>Homo</i>	-3.8	-2.8	1.65	0.05
KNM-ER 2593	m frag	Hominini indet.	-0.8	-0.4	1.55	0.05
KNM-ER 42705	m3 frag	Hominini indet.	-2.0	-2.4	1.59	0.04
0.01 Ma						
KNM-LT 13700b	rt m2	<i>H. sapiens</i>	-6.9	-0.9	0.01	0.005
KNM-LT 13700b	rt m3	<i>H. sapiens</i>	-5.4	-1.3	0.01	0.005
KNM-LT 27714B	lt m2	<i>H. sapiens</i>	-2.2	-0.9	0.01	0.005
KNM-LT 27719C	rt M2	<i>H. sapiens</i>	-2.6	-1.5	0.01	0.005
KNM-WT 38400	lt m1	<i>H. sapiens</i>	-6.8	-0.9	0.01	0.005

Specimen numbers are from the National Museums of Kenya (KNM). m frag, molar fragment; lt, left; rt, right; m, lower molar; M, upper molar; p, lower premolar; P, upper premolar.

Table S2. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values for tooth enamel from primates in East and Central Africa

Sample	Species	Tooth	$\delta^{13}\text{C}$	$\delta^{13}\text{C}_{1750}$	$\delta^{18}\text{O}$	Year of death	Country	Location	Source
ICCN-KB-064	<i>Gorilla beringei</i>	M1	-16.8	-15.1	-3.0	2004	DRC	Kahuzi-Biega	This study
ICCN-KB-065	<i>G. beringei</i>	M1	-17.8	-16.2	-3.8	1996	DRC	Kahuzi-Biega	This study
ICCN-KB-066	<i>G. beringei</i>	M3	-14.0	-12.5	-4.1	1997	DRC	Kahuzi-Biega	This study
ICCN-KB-070	<i>G. beringei</i>	M3	-15.1	-13.3	-3.9	2003	DRC	Kahuzi-Biega	This study
ICCN-KB-078	<i>G. beringei</i>	m1	-15.9	-14.3	-3.8	1997	DRC	Kahuzi-Biega	This study
ICCN-KB-078	<i>G. beringei</i>	m2	-14.1	-12.6	-3.6	1997	DRC	Kahuzi-Biega	This study
ICCN-KB-088	<i>G. beringei</i>	m2	-14.2	-12.6	-3.0	1997	DRC	Kahuzi-Biega	This study
ICCN-KB-089	<i>G. beringei</i>	m3	-14.9	-13.3	-5.2	1997	DRC	Kahuzi-Biega	This study
L3150 E	<i>G. beringei</i>	P3	-15.4	-14.6	-4.3	1972	DRC	Kahuzi-Biega	This study
ICCN-WCS-022	<i>G. beringei</i>	P4	-14.8	-13.2	-2.9	1996	DRC	Itombwe massif	This study
ICCN-WCS-040	<i>G. beringei</i>	M3	-13.3	-11.7	-5.7	1996	DRC	Itombwe massif	This study
ICCN-WCS-074	<i>G. beringei</i>	m3	-13.0	-11.5	-2.5	1996	DRC	Itombwe massif	This study
ICCN-WCS-075	<i>G. beringei</i>	C	-14.3	-12.8	-4.5	1996	DRC	Itombwe massif	This study
ICCN-WCS-075	<i>G. beringei</i>	M2	-14.4	-12.9	-3.5	1996	DRC	Itombwe massif	This study
ICCN-WCS-076	<i>G. beringei</i>	M2	-15.5	-13.9	-4.6	1996	DRC	Itombwe massif	This study
CEF-048	<i>Cercopithecus</i> sp.	M3	-15.8	-14.3	-0.2	1995	DRC	Ituri	1
CEF-249	<i>Cercopithecus</i> sp.	M3	-16.9	-15.3	0.7	1995	DRC	Ituri	1
ICCN-KB-072	<i>Cercopithecus</i> sp.	M3	-14.9	-13.2	-2.9	2002	DRC	Kahuzi-Beiga	This study
ICCN-KB-072	<i>Cercopithecus</i> sp.	M2	-14.6	-12.8	-4.2	2002	DRC	Kahuzi-Beiga	This study
ET05-AA-M152	<i>C. aethiops</i>	Im2	-14.3	-13.5	6.1	1965	Ethiopia	Bulbula	2
ET05-AA-M151	<i>C. aethiops</i>	IM	-14.0	-13.2	5.4	1965	Ethiopia	Bulbula	2
ET05-AA-M299	<i>C. aethiops</i>	M	-13.4	-12.6	3.8	1965	Ethiopia	Bulbula	2
ET05-AA-M191	<i>C. aethiops</i>	m2	-12.3	-11.5	2.6	1965	Ethiopia	Debre Zehir	2
ET05-AA-M146	<i>C. neglectus</i>	M2	-16.5	-15.7	0.2	1965	Ethiopia	Godare	2
CEF-239	<i>Colobus</i> sp.	M3	-16.1	-14.6	4.9	1995	DRC	Ituri	1
JAH-015	<i>Colobus</i> sp.	m3	-16.5	-15.0	6.8	1995	DRC	Ituri	1
CEF-182	<i>Colobus</i> sp.	M3	-16.5	-15.0	0.1	1995	DRC	Ituri	1
L15359	<i>Colobus</i> sp.	C	-17.0	-16.3	-0.2	1966	DRC	unk	This study
ICCN-KB-063	<i>Colobus</i> sp.	M2	-14.6	-12.8	-1.5	2004	DRC	Kahuzi-Beiga	This study
CEF-135	<i>Pan troglodytes</i>	M2	-16.0	-14.5	-1.1	1995	DRC	Ituri	1
WCS-041	<i>P. troglodytes</i>	M2	-15.1	-13.5	-3.1	1996	DRC	Itombwe massif	This study
CEF-207	<i>Papio anubis</i>	M3	-17.1	-15.5	-1.4	1995	DRC	Ituri	1
K98-Lai-306-M3	<i>P. anubis</i>	M3	-4.1	-2.5	4.4	1997	Kenya	Laikipia	This study
K98-Lai-344	<i>P. anubis</i>	M3	-6.8	-5.2	4.9	1998	Kenya	Laikipia	This study
K97-231-Lai	<i>P. anubis</i>	M2	-4.8	-3.3	8.1	1997	Kenya	Laikipia	This study
87-OLOR-625	<i>P. anubis</i>	M2	-10.5	-9.2	4.3	1987	Kenya	Olgorgesailie	This study
95-OLOR-235	<i>P. anubis</i>	m2	-11.1	-9.6	4.1	1995	Kenya	Olgorgesailie	This study
K98-Tsv-147	<i>P. anubis</i>	m2	-8.8	-7.4	1.7	1994	Kenya	Tsavo	This study
K98-Tsv-148	<i>P. anubis</i>	m3	-12.3	-10.8	1.5	1994	Kenya	Tsavo	This study
SU96:5	<i>P. anubis</i>	M3	-12.5	-10.9	4.8	1996	Kenya	Turkana	This study
L4180	<i>P. anubis</i>	C	-13.6	-12.9	-2.3	1958	DRC	eastern DRC	This study
L5450	<i>P. anubis</i>	C	-13.2	-12.5	-1.5	1959	DRC	Kisoro/Rutsuru	This study
L5148	<i>P. anubis</i>	P4	-11.3	-10.5	-2.7	1959	DRC	Chagulube/Kalehe	This study
L5593	<i>P. anubis</i>	I	-10.3	-9.6	-2.1	1959	DRC	Nyamukubi/Kalehe	This study
ET05-BM-09	<i>P. anubis</i>	M3	-14.1	-12.4	-1.3	2000	Ethiopia	Bale NP	2
ET05-MAGO-02	<i>P. anubis</i>	M3	-14.0	-12.3	-0.3	2000	Ethiopia	Mago NP	2
ET05-NCHSR-08	<i>P. anubis</i>	M2	-14.5	-12.8	3.9	2000	Ethiopia	Nechisar NP	2
ET05-NCHSR-14	<i>P. anubis</i>	M3	-11.0	-9.3	-1.5	2000	Ethiopia	Nechisar NP	2
ET05-NCHSR-14	<i>P. anubis</i>	P	-13.2	-11.5	1.3	2000	Ethiopia	Nechisar NP	2
LS-1	<i>Papio hamadryas</i>	M3	-6.4	-4.7	-0.6	2000	Ethiopia	Awash NP	2
LS-2	<i>P. hamadryas</i>	M3	-12.1	-10.4	1.1	2000	Ethiopia	Awash NP	2
LS-3	<i>P. hamadryas</i>	M3	-11.8	-10.1	-0.2	2000	Ethiopia	Awash NP	2
GON04M-88	<i>P. hamadryas</i>	m3	-12.1	-10.4	0.6	2000	Ethiopia	Gona	2
GON06NO-03	<i>P. hamadryas</i>	m2	-11.9	-10.2	1.9	2000	Ethiopia	Gona	2
GON06NO-03	<i>P. hamadryas</i>	m3	-12.0	-10.3	2.2	2000	Ethiopia	Gona	2

Measured $\delta^{13}\text{C}$ values have been corrected to 1750 based on the estimated year of death of the individual; this correction is because of the change in the $\delta^{13}\text{C}$ value of the atmosphere from fossil fuel burning (3, 4). DRC, Democratic Republic of Congo.

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Table S3. Stratigraphic information used to determine age estimates for hominin fossils in the Turkana Basin

Specimen	Formation	Member	Area/locality	Marker	Level	Age (Ma)	±
KNM-ER 729	Koobi Fora	Okote	Area 8	BPT	2	1.53	0.03
KNM-ER 730	Koobi Fora	KBS	Area 103	LKF	-5	1.54	0.05
KNM-ER 732	Koobi Fora	KBS	Area 10	Upper KBS		1.78	0.10
KNM-ER 733	Koobi Fora	Okote	Area 8	SubNILT	-4	1.52	0.03
KNM-ER 801	Koobi Fora	Okote	Area 6A	LIL	-8	1.59	0.04
KNM-ER 802	Koobi Fora	Okote	Area 6A	LIL	-8	1.59	0.04
KNM-ER 807	Koobi Fora	Okote	Area 8A	6159	-2	1.52	0.05
KNM-ER 808	Koobi Fora	Okote	Area 8	SubNILT	-5	1.52	0.03
KNM-ER 809	Koobi Fora	Okote	Area 8	BPT	2	1.53	0.03
KNM-ER 810	Koobi Fora	KBS	Area 104	A2	-4	1.73	0.03
KNM-ER 816	Koobi Fora	KBS	Area 104	A2	-4	1.73	0.03
KNM-ER 818	Koobi Fora	Okote	Area 6	ILN	-2	1.50	0.05
KNM-ER 820	Koobi Fora	Okote	Area 1	SubNILT	-2	1.51	0.05
KNM-ER 992	Koobi Fora	Okote	Area 1	ILN	10	1.46	0.03
KNM-ER 1171	Koobi Fora	Okote	Area 6A	LIL	-8	1.59	0.04
KNM-ER 1469	Koobi Fora	Upper Burgi	Area 131	KBS	-13	1.93	0.04
KNM-ER 1478	Koobi Fora	KBS	Area 105	KBS	cc	1.82	0.05
KNM-ER 1479	Koobi Fora	KBS	Area 105	KBS	cc	1.82	0.05
KNM-ER 1482	Koobi Fora	Upper Burgi	Area 131	KBS	-26	1.99	0.05
KNM-ER 1483	Koobi Fora	Upper Burgi	Area 131	KBS	-4	1.89	0.03
KNM-ER 1593	Koobi Fora	KBS	Area 12	KBS	ca. C4	1.80	0.07
KNM-ER 1802	Koobi Fora	Upper Burgi	Area 131	GPC	—	1.97	0.03
KNM-ER 1804	Koobi Fora	KBS	Area 104	A2	-4	1.73	0.03
KNM-ER 1805	Koobi Fora	KBS	Area 130	KBS	11	1.76	0.04
KNM-ER 1806	Koobi Fora	KBS	Area 130	KBS	11	1.76	0.04
KNM-ER 1808	Koobi Fora	KBS	Area 103	A6	-2	1.59	0.03
KNM-ER 1814	Koobi Fora	KBS	Area 127	KBS		1.67	0.10
KNM-ER 1819	Koobi Fora		Area 3	None		1.60	0.10
KNM-ER 2593	Koobi Fora	Okote	Area 6	MIL	+1	1.48	0.03
KNM-ER 2599	Koobi Fora	KBS	Area 15	KBS	2	1.86	0.03
KNM-ER 2600	Koobi Fora	KBS	Area 130	KBS	cc	1.82	0.05
KNM-ER 2607	Koobi Fora	KBS	Area 105			1.73	0.10
KNM-ER 3733	Koobi Fora	KBS	Area 104	White	-1	1.65	0.05
KNM-ER 3734	Koobi Fora	KBS	Area 105	GPC	1	1.95	0.03
KNM-ER 3737	Koobi Fora	Okote	Area 6A	LIL	-8	1.59	0.04
KNM-ER 3887	Koobi Fora	Okote	Area 1	ILN	10	1.46	0.03
KNM-ER 3952	Koobi Fora	KBS	Area 105	KBS	cc	1.82	0.05
KNM-ER 5431	Koobi Fora	Tulu Bor	Area 203	TUL		3.20	0.10
KNM-ER 6080	Koobi Fora	Okote	Area 8A	SubNILT	-4	1.52	0.03
KNM-ER 6082	Koobi Fora	Okote	Area 8A	ILN	-2	1.50	0.04
KNM-ER 7330	Koobi Fora	KBS	Area 107	C4	0	1.83	0.04
KNM-WT 8556	Nachukui	Lomekwi	LO5	TUL	17	3.24	0.10
KNM-ER 13750	Koobi Fora	KBS	Area 105	KBS	cc	1.82	0.05
KNM-ER 15940	Koobi Fora	KBS	Area 104	A2	-4	1.73	0.03
KNM-ER 15951	Koobi Fora	Okote	Area 8	SubNILT	-3	1.52	0.03
KNM-WT 16005	Nachukui	Lokalalei	Kangatukuseo	KU2		2.45	0.05
KNM-WT 16006	Nachukui	Lomekwi	LO4	TUL	5	3.37	0.05
KNM-WT 17000	Nachukui	Lokalelei	LO1	LKL	0	2.52	0.05
KNM-WT 17396	Nachukui	Kaito	Kokiselei KS1			1.77	0.03
KNM-ER 18540	Koobi Fora	Lonyumun	Area 261	MOI	-5	4.00	0.05
KNM-ER 20420	Koobi Fora	Lonyumun	Area 261	MOI	-5	4.00	0.05
KNM-WT 22936	Nachukui	South Turkwel				3.40	0.20
KNM-LT 23181	Nachukui	Kaiyumung				3.30	0.20
KNM-LT 23182	Nachukui	Kaiyumung				3.30	0.20
KNM-LT 25936	Nachukui	Kaiyumung				3.30	0.20
KNM-KP 29287	Kanapoi			KAN	3	4.06	0.04
KNM-ER 30200	Koobi Fora	Lonyumun	Area 261	MOI	-5	4.00	0.05
KNM-KP 30498	Kanapoi	—				4.12	0.04
KNM-KP 30502	Kanapoi	—				4.12	0.04
KNM-ER 30745	Koobi Fora	Lonyumun	Area 261	MOI	-5	4.00	0.05
KNM-KP 35839	Kanapoi	—				4.12	0.04
KNM-KP 35840	Kanapoi	—				4.12	0.04
KNM-KP 35842	Kanapoi	—				4.12	0.04

