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METHODS

Geochemical mapping. Fossil teeth StS 28 (n=3) and StS 51 (n=2) (and all other specimens presented in this paper) were sectioned with a high-precision diamond saw at the cusp's apex, then surface polished to 10 microns smoothness (Figs. S2 & S3). Each tooth was then introduced into the laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) chamber for analysis (Fig. S4). LA-ICP-MS was used for trace elemental mapping analyses of the sample according to the published protocol previously used for Neanderthal breastfeeding analyses⁴. SOLARIS at Southern Cross University (ESI NW213 coupled to an Agilent 7700 ICP-MS) and a separate system at Icahn School of Medicine at Mount Sinai in New York (ESI NWR193 ArF excimer laser coupled to an Agilent 8800 ICP-MS) were used to map the samples, with the laser beam rastered along the sample surface in a straight line. The laser spot size was 40 μm or 35 μm , laser scan speed of 80 $\mu\text{m}\cdot\text{s}^{-1}$ or 70 $\mu\text{m}\cdot\text{s}^{-1}$, laser intensity of 80% or 60%, respectively, and an ICP-MS total integration time of 0.50 s produced data points that corresponded to a pixel size of approximately 40 \times 40 μm or 35 \times 35 μm , respectively. NIST610, NIST612 and NIST614 (certified standard reference materials) were used to assess signal drift.

Isotopic profiling. $^{87}\text{Sr}/^{86}\text{Sr}$ was measured by a laser ablation multi-collector inductively coupled plasma mass spectrometer (LA-MC-ICP-MS) at the University of Wollongong (WIGL laboratory) (Thermo Neptune Plus connected to an ESI NWR193 ArF excimer laser ablation system). Both enamel and dentine of StS 28 and StS 51 were analysed with nine and six 150- μm ablation spots (respectively), a dwell time of 50 s, 20 Hz frequency and 40% laser intensity. Sample aerosol was carried to the ICP-MS using a mixture of He and N₂. The following isotopes were collected in static mode: ^{82}Kr , ^{83}Kr , ^{84}Sr , ^{85}Rb , ^{86}Sr , $^{172}\text{Yb}^{++}$, ^{87}Sr , ^{88}Sr and $^{177}\text{Hf}^{++}$. Each isotope was collected using cycles of 1s each. Data reduction (including a background subtraction, mass bias, Rb/Sr and Ca argide/dimmer corrections) were performed using Iolite³⁶ with the CaAr interference correction Sr isotope scheme³⁷. A seal tooth and a clam shell with modern seawater $^{87}\text{Sr}/^{86}\text{Sr}$ value (0.7092)³⁸ were analysed four times at the start and end of each session and used as a matrix-matched primary standard to further correct $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Image processing. For elemental maps obtained by LA-ICP-MS, ablation lines were extracted in the form of a .csv files generated by the MassHunter Workstation software (Agilent). Each file was then imported into the interactive R Shiny application "shinyImaging" (the application can be accessed at <http://labs.icahn.mssm.edu/lautenberglab/>), which transforms each isotope into a separate file containing the counts per second (CPS) values of one element and is organised as a matrix (number of ablation lines multiplied by the number of ablation spots per ablation line). For each element, gas blank CPS (median value in pixels per ablation spot) collected during the first 10 s of each analysis (gas blank) were used as background and subtracted from the rasterstack. Background around the teeth (signal arising from the encasing resin) was converted to white coloration (no intensity) to increase clarity of the figures by isolating the dental tissue from its surroundings. Colour scales were applied using the linear blue-red Lookup Table. For Figure 3C, the StS 51 canine enamel and dentine were set to a slightly different scale to allow clearer identification of the different bands. The sliding coloured scale was adjusted accordingly.

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Table S1 – List of primate and non-primate mammals from the South African savanna biome (grassland-dominated ecosystem) used for geochemical mapping comparison.

Common name Species Trophic level Tooth

identification

Springbok (bovid) *Antidorcas marsupialis* herbivore second molar

Caracal (felid) *Caracal caracal* carnivore premolar 4

Baboon (monkey) *Papio ursinus* opportunistic feeder first and third molars

Bush pig (suid) *Potamochoerus porcus* omnivore premolar 3

Fox (canine) *Otocyon megalotis* carnivore second molar

SUPPLEMENTARY DISCUSSION

MATERIAL DESCRIPTION

The UNESCO World Heritage Site ‘Fossil Hominids of South Africa’, colloquially known as the Cradle of Humankind, is situated ~50 km north-northwest of Johannesburg in the Blaaubank River valley, South Africa. The dolomitic limestone of the Malmani Subgroup formed some 2.6 Ga ago³¹ and provided an ideal environment for the formation of cave sites which allowed for the formation of palaeontological deposits during (at least) the terminal Pliocene and early Pleistocene. Specifically of importance to palaeoanthropology, the Sterkfontein Caves, considered the richest assemblage of *Australopithecus* fossils in South Africa, is a cave site located in the southern portion of the designated Cradle region. The Sterkfontein cave system has been continuously excavated since the first expedition in 1936³², following the discovery of the first adult *Australopithecus* specimen. The site has a complicated stratigraphy, with several depositional and post-depositional processes³³. The Member 4 (M4) (ED Fig. 1) deposits have produced the majority of the *Australopithecus* fossils, including the iconic first adult *Australopithecus* Mrs. Ples (StS 5) and the StS 14 skeleton³⁴. All fossil remains with the StS catalogue number, such as the dental fossil remains in this study, were excavated from the Type Site in association with the M4 deposits.

NURSING BEHAVIOUR IN MODERN APES & *A. AFRICANUS*

Modern primates have been shown to have a broad range of nursing behaviours intervals, from lengthy breastfeeding and weaning sequence in gorilla and chimpanzees^{39,40,41}, as well as the unique cyclical breastfeeding in *Pongo* for the first 8 years of the offspring life⁵. In contrast, modern humans are known to have a short nursing duration averaging 12 months in industrial societies and about 2 years in prehistoric groups^{39,42,43}. The short nursing period of immature *Homo sapiens* infant, in particular the early weaning contrast with the late maturation of the offspring compare to other extant hominids. Interestingly, a similar nursing behaviour was observed in several *Homo neanderthalensis* children dating back to about 120ka to 200ka^{5,44}. Yet, little is known about the evolution of the characteristic early weaning and late maturation of modern humans. Here, *A. africanus* shows a short exclusive breastfeeding phase (~9 months) but the age at weaning is unfortunately harder to observe due to the cyclical Ba and Sr signals observed, similar to modern *Pongo*. Yet, the species has been described to reach sexual maturity late, and to depend on adults for food and safety upon adult specimens for a long period of time^{40,45}. Furthermore, with the animal under

sever seasonal food stress, it appears plausible that the cyclical signal observed in StS 28 and StS 51, linked to stress and fluctuation of nutritious food access, also contains a long weaning phase spanning several years with periodic increase of maternal milk intake. (see ED Fig. 5 and discussion below).

BIOAVAILABILITY OF BARIUM FROM BREASTMILK VS NON-MILK FOODS

The bioavailability of divalent cations such as barium and strontium is complex, particularly in terms of their incorporation pathways into bone and teeth crystal structure. The specific pathways of these elements into the body via different foods has not been examined in detail, however it seems to be clear that Ba and Sr also have very different bioavailability and uptake depending on their source.

There is a scarcity of information on the comparative bioavailability of non-essential elements in milk and plant-based foods. However, the trend observed in captive macaque data showed a decrease in Ba/Ca with the introduction of non-milk foods⁴. Calcium in milk is more absorbable and bioavailable than Ca from other foods such as fish and vegetables⁴⁶. It has been proposed that phosphopeptides released from casein digestion increase the stability and solubility of Ca and other divalent cations in milk, improving their absorbability^{47,48}. Given the chemical similarities of Ca and Ba, it is likely that phosphopeptides also increase the bioavailability of Ba in milk.

Bioavailability in vegetables is dependent on the properties of the element as well as the plant species⁴⁹ and therefore the bioavailability of Ba in different plants may vary significantly. For example, despite the high Ba content of Brazil nuts (as high as 4 mg g⁻¹), no toxic effects to humans have been reported, which is likely due to the major fraction of Ba in the nuts being insoluble, with low bioavailability⁵⁰.

Consequently, while many plant-based foods have higher Ba/Ca content than milks⁵¹, their supplementation of an infant's diet reduce the available circulating Ba due to low Ba bioavailability. It is important to clarify that the higher Ba signal in teeth during periods of milk-intake is not due to an enrichment of Ba in milk. Rather it is the increased bioavailability of Ba in milk, compared to non-milk foods, that leads to higher levels being incorporated into teeth during periods of milk intake. Other sources may contribute to the Ba signal, but the proportion of Ba from non-milk sources is likely to be small due to poor bioavailability.

Ba follows a similar biopurification process to that of Ca and Sr, decreasing with trophic levels⁵¹. Therefore, animals with a predominantly plant-based diet, such as modern *Pongo* and perhaps *A. africanus*, tend to ingest more Ba than carnivorous mammals. A relatively small amount of Ba is expected to be absorbed from non-milk foods and will predominantly be stored in the bones and teeth, where it can be released during bone remodelling, particularly during lactation. Yet little contribution is expected from the infant tissues. Ba banding from the remodelling of infant bones would only occur in cases of extreme starvation and not in calorie deficiency periods. Even during long periods of food deprivation there is little bone loss, although there is a significant loss of body fats⁵². It is, therefore, unlikely that Ba in infant teeth originates from their own bones. However, there is evidence in humans that even during periods of full food availability, circulating Ca and its analogues (such as Pb and Ba) are derived from readjustment of the mother's bones during pregnancy and lactation, rather than directly from the diet due to the increased Ca requirements during these periods⁵³.

Adequate Ca intake via supplements can reduce skeletal mobilisation.

CYCLICAL BARIUM BANDING IN SOUTH AFRICAN MAMMALS

Animals living in the tropical grassland-dominated ecosystems (frequently referred to as the savanna biome) face important seasonal rainfall oscillations which impact their ecosystem and induce successive periods of increased and decreased food availability^{13,15, 54}. It can be anticipated that the low rainfall seasons correspond to the

nutritional stress observed in *A. africanus*, and further research is needed to confirm this hypothesis. During this period australopiths would have experienced depleted food sources, yet the isotopic analyses do not indicate large movement in the landscape. Occupying a depauperated area, while restricting the amount of nutritional food, also likely meant reduced overall mammal biomass across trophic levels including less support for predators. By diversifying their diets and food sources, *Australopithecus africanus* would have been able to sustain living in such environments, lessening predatory pressure, and therefore increasing survival chances. Some non-migrating mammals inhabiting the landscape had to adapt their diet to the seasonal changes, including the use of fallback resources during food shortage periods^{13,15,54}. Here we have analysed a range of modern mammals, including carnivores (*felid* 5B, and *canid* 5E), herbivores (*bovid* 5A), omnivores (*suid* 5D) and opportunistic feeders (*baboon* 5C and F) (see ED Fig. 5 and Table S1). All of the teeth analysed show some degree of Ba/Ca and Sr/Ca banding. Compared to the other animals, carnivores showed the lowest difference between high and low Ba bands. This is likely due to the low Ba absorption predicted by their high trophic level. The mammals analysed here are known to have short nursing period of a few months, up to one year for *Papio ursinus*¹⁵. Cyclical Ba bands are observed in the third molar of a baboon (see ED Fig. 5C), well beyond any known breastfeeding behaviour for this species. A similar cyclical pattern of Ba/Ca, Sr/Ca and Li/Ca found in modern wild *Pongos* was attributed to oscillations in breast milk intake as this species is known to have prolonged nursing. Seasonal variation was described as the primary driver for resource shortage resulting in a high periodicity of nursing cycles to supplement calorie deficiency. In *A. africanus* the banding pattern is similar to both the *Papio* and the *Pongo* specimens, especially the later which show a very similar spatial relationship between all three elements (Li, Sr and Ba). Thus, it cannot be excluded that part of the signal observed in *A. africanus* teeth StS28 and StS51 could also reflect variation of breast milk intake conjointly with seasonal food shortage signal. This hypothesis could explain the rather abrupt change from breastfeeding to periodic banding recorded after only ~1 year of nursing the australopiths infant. Furthermore, the presence of highly cyclical bands of the synchronous Li/Ca signal, also observed in wild *Pongo* (see ED Fig. 9) could be also an indication of recurring nursing cycles.

DIAGENETIC PROCESS AND SIGNAL INTERFERENCES

The typical biogenic Li/Ca, Sr/Ca and Ba/Ca bands in all StS 28 and StS 51 samples are in strong contrast to elements, often far more mobile, which follow a typical and well-known diffusion pathway that has a broad signature that is unmistakably different from that of dental growth patterns⁵⁵ (ED Fig. 3 & 4). In fact, the signal in the form of bands that can be followed from the dentine to the enamel is extremely unlikely to be created by diagenetic processes. Secondary incorporations of trace elements are typically described by diffusion fronts from the roots to the enamel-dentine junction (EDJ) (with sometimes enrichment at the junction) and on the outer layer of the enamel in contact with the sediments⁵⁵. Because diffusion processes are strongly linked to water circulation, fractures are preferential pathways for elemental mobility. Characteristic patterns of leaching or broad elemental diffusion can be seen associated with these diagenetic features⁵⁵. This characteristic pattern can be observed for most elements in the enamel and dentine directly in the vicinity of the fractures. ⁵⁵Mn, ⁶³Cu, ²³⁸U and rare earth elements are representative of this specific secondary diffusion through enamel and dentine cracks. Additionally, phosphorous is often measured to quantify potential dissolution episodes of dentine sections through the attack of acidic water. Naturally occurring in hydroxyapatite crystals in teeth, P is mostly absent in reprecipitated crystals of calcite. Large zones in the dentine showing significant depletion

of P are considered to be the results of dissolution and re-crystallisation of dentine⁵⁶. All *A. africanus* teeth show small characteristic diagenetic processes, that do not obstruct the biogenic banding (Fig. 1, 2, 3, ED Fig. 3 and 4).

The Sr, Ba and Li biogenic signals observed in StS 28 and StS51 appear to be marginally influenced by secondary processes during burial. This confirms the diagenetic assessment of another study done on similar teeth from the same sites, for which little diagenetic influences were identified⁵⁷. Ultimately, the strongest argument against diagenetic influence on the banding is the concordance of banding patterns between teeth from the same individual. Both the permanent canine and premolar teeth (which likely formed over similar time zones in infant life) of StS 51, show matching temporal banding patterns for all three elements – strong evidence of biogenic signals (ED Fig. 4). Similarly, the trace elemental banding patterns of StS 28 permanent upper and lower first molar show similar banding patterns (ED Fig. 3).

Although a diagenetic process did not significantly alter the pattern of distribution for Sr and Ba, the nursing signal can be complicated by additional elemental mobilisation from stress episodes⁵⁸. Whereas tissues such as muscles and fat account for only 1% to 2% of the barium stored in the body⁵⁹, skeletal reserves can release a large amount of barium during acute illness or starvation⁵⁸. Acute stress events leave distinctive discrete bands in dental tissues, which can be distinguished from the broader bands associated with nursing (ED Fig. 3 and 4). Such narrow stress bands are believed to be the additional discrete bands in the Sr/Ca signal and to a lesser extent in the Ba/Ca pattern. Considering their age of about 2 Ma, both specimens (StS 51 and StS 28) reveal a surprisingly pristine elemental record of two australopiths.

LITHIUM INCORPORATION AND PATHWAYS

Lithium has complex, multifactorial and inter-correlated biochemical mechanisms with other elements, enzymes, hormones, vitamins, growth, fat accumulation and body weight⁶⁰. Lithium was also shown to be critical for lactating mothers and the development of young adults. The physiological pathway in primates remains obscure, apart from modern medical studies on patients treated for bipolar disorder. It is not the first time we see Li/Ca bands clearly overlapping with the Ba/Ca nursing signals⁵. This pattern is not surprising since Li has been measured in breast milk and in nursing infants⁶¹. However, some of the Li/Ca signal measured in the *Pongo* and *A. africanus* teeth seems to precede the apex of Ba/Ca bands (Fig. 3 & ED Fig. 8).

In the human body, Li is predominantly stored in bone tissue; specifically, Li accumulates in the crystal structure (60%) and in the hydrosphere (40%). The latter location makes Li more readily mobilised during physiological remodelling⁶². Consequently, it is speculated that the mobilization of hydrosphere Li could foreshadow that of Ba and Sr in the bloodstream. However, similar to wild *Pongo*, it is unlikely that an organism would evolve a response where maternal health could be compromised by remobilising skeletal tissue repeatedly while nutritionally supporting their young⁵.

Diet could also influence the Li/Ca signal accumulation and deposition. Lithium concentration varies greatly in the environment, from traces in soil (7 to 200 ng/g) to much greater concentration in water⁶⁰. Plants and parts of plants have also shown strong fluctuation in Li concentration⁶⁰. A sudden change of diet toward a specific food source rich in Li could be responsible for the accumulation of the element in breast milk.

Although evidence suggests that the bioavailability of Ba from non-milk foods is low⁴ and therefore does not impart an appreciable signal in developing teeth, the bioavailability of Li from such foods is unknown. Therefore, whether introduction of a Li-rich food source would increase Li in teeth is unknown.

In a scenario where resources become scarce, immature individuals who are particularly vulnerable to food shortage would increase their volumetric milk intake to compensate for the loss of calories. This was one interpretation of the cyclical Ba/Ca pattern observed in the teeth. Both infant and mother would also most certainly re-orient their diet to fallback resources, poor in calories but perhaps richer in protein, as seen in wild *Pongo* individuals^{18,19}. In this case, the mother, already facing a depletion of caloric intake herself from shortage of food, would nevertheless be required to produce additional milk. Under such caloric deficit, the mother could face certain weight loss corresponding to the resorption of tissues, such as muscles and fat reserves, and perhaps even some of the hydrosphere part of her bone structure⁶³. This could trigger the mobilization of Li in the mother's bloodstream and ultimately in the breast milk. Bodymass fluctuation in the nursing mother would translate into banding of Li/Ca in the offspring's tooth. With 40% of Li in the hydrosphere of the bone readily available, Li could perhaps occasionally accumulate earlier in breast milk before the mother is able to increase the volumetric amount of breast milk, which corresponds to the Ba/Ca banding in the offspring tooth. An alternative hypothesis under the same scenario of environmental pressure and increase in nursing is that the fallback resources are enriched in Li. This would be a more likely scenario, considering that *Pongo* favors higher-protein food as fallback resources to avoid severe caloric dearth^{18,19}. A larger amount of Li in the body could then be explained by the benefit of the element against protein deficiency²⁶. Unfortunately, natural accumulation of Li in the body through nutrition remains poorly understood, although metabolically the link between fat accumulation and Li concentration has been demonstrated in patients treated for depression^{64,65}. Nevertheless, recurring Li banding has not been observed commonly in modern human teeth and was not detected in previously measured extinct *Homo* samples⁴. Perhaps the Li signal might be clearly distinguishable only during nursing, specifically while breastfeeding under food stress and use of Li rich fallback resources. In any case, the Li banding observed here points toward some degree of environmental pressure and physiological adjustment by *A. africanus*, similar to what has been seen in wild *Pongo*.

Speculatively, one can wonder whether natural selection might have favored efficient Li accumulation or storage processes in primates facing recurrent environmental pressure. This would allow offspring to receive a greater amount of Li, which seems to facilitate fat accumulation^{64,65} and to reduce protein-deficient conditions²⁶, which is an undeniable advantage for infants during food shortage and caloric deficiency.

CONSIDERATIONS OF BARIUM AND STRONTIUM CORRELATIONS

Barium and strontium did not show a consistent correlative or reciprocal pattern either within a tooth or across teeth. As demonstrated in ED Fig. 6A, at times, Ba and Sr are synchronous, rising and falling in unison, while at other times, the peaks and valleys are slightly offset between elements. This could be indicative of exposure source. For example, when Ba and Sr are synchronous, both elements must be derived from the same source, such as skeletal remineralisation. When the elements become asynchronous, this likely indicates a change in food source where the content or bioavailability of either element is different, such as the start of solid food supplementation. Further research into the synchronicity of Ba and Sr signals is needed before conclusive interpretations regarding dietary source can be made. Specifically, determining the bioavailability of Ba and Sr in different food sources is paramount to reliably attributing cyclical patterns to dietary sources, including teasing cyclical milk intake from other seasonal food sources.

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