

Barium distributions in teeth reveal early-life dietary transitions in primates

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Early-life dietary transitions reflect fundamental aspects of primate evolution and are important determinants of health in contemporary human populations^{1,2}. Weaning is critical to developmental and reproductive rates; early weaning can have detrimental health effects but enables shorter inter-birth intervals, which influences population growth³. Uncovering early-life dietary history in fossils is hampered by the absence of prospectively validated biomarkers that are not modified during fossilization⁴. Here we show that large dietary shifts in early life manifest as compositional variations in dental tissues. Teeth from human children and captive macaques, with prospectively recorded diet histories, demonstrate that barium (Ba) distributions accurately reflect dietary transitions from the introduction of mother's milk through the weaning process. We also document dietary transitions in a Middle Palaeolithic juvenile Neanderthal, which shows a pattern of exclusive breastfeeding for seven months, followed by seven months of supplementation. After this point, Ba levels in enamel returned to baseline prenatal levels, indicating an abrupt cessation of breastfeeding at 1.2 years of age. Integration of Ba spatial distributions and histological mapping of tooth formation enables novel studies of the evolution of human life history, dietary ontogeny in wild primates, and human health investigations through accurate reconstructions of breastfeeding history.

Weaning, the dietary transition from breast milk to exclusive solid food intake, concludes several years earlier in modern humans than in other great apes^{5,6}. Cross-cultural studies of nonindustrial societies reveal remarkable variation in weaning practices⁷. However, among non-human primates, dietary transitions remain understudied^{8,9}. In addition to the paucity of comparative primate data, our understanding of the evolution of human weaning has been limited by difficulties in assessing the precise timing and nature of dietary transitions during infancy³. Dental hard tissues are particularly valuable for reconstructing diet as they contain precise temporal and chemical records of early life⁴. Teeth begin forming *in utero*, record birth as the neonatal line, and manifest daily growth lines, which allow chronological ages to be determined at various positions within tooth crowns and roots (Supplementary Fig. 1).

We propose that micro-spatial analysis of barium/calcium ratios (Ba/Ca) in dental tissues represents a powerful approach to assess dietary transitions. Whereas prenatal Ba transfer is restricted by the placenta, marked enrichment occurs immediately after birth from mother's milk or infant formulas, which contain higher Ba levels than umbilical cord sera¹⁰. In response to these variations in dietary Ba exposure, Ba/Ca in enamel and dentine should increase at birth, remain elevated for the duration of exclusive breastfeeding and rise further with introduction of infant formula. Circulating Ba levels are

expected to change at weaning as Ba (and Ca) content and bioavailability is markedly different across plant and animal food sources^{11,12}. To test this hypothesis, we investigated Ba/Ca patterns in teeth from human children for whom early life diets were recorded prospectively, and in teeth from captive macaques in which maternal milk was collected and suckling behaviour observed.

High-resolution elemental analysis by laser ablation-inductively coupled plasma-mass spectrometry revealed marked Ba/Ca increases in enamel and dentine formed immediately after birth in human deciduous teeth ($n = 22$ of 25 individuals) (Fig. 1a–c). In 9 of 13 children who were initially breastfed and given infant formula later, two distinct zones of Ba/Ca distribution were apparent in postnatal regions formed before crown completion (Fig. 1d, e). Histological analysis (Supplementary Fig. 2) revealed a close correspondence between the formation time of the first zone and maternal reports of exclusive breastfeeding. Four individuals who continued to consume breast milk for a long period (9–42 months) after the introduction of formula at 1–2 months did not show two distinct Ba/Ca zones in enamel or dentine. In children for whom formula was introduced almost immediately after birth and who were breastfed for less than 1 month (Fig. 1e), the first Ba/Ca zone immediately adjacent to the neonatal line was narrower than in infants exclusively breastfed for longer. Individuals who were exclusively breastfed during the entire period of tooth crown formation ($n = 7$ of 25; Fig. 1f) showed an increase in Ba/Ca across the neonatal line, but as expected, no subsequent Ba/Ca zoning was apparent in postnatally formed dentine (as seen in infants who made a transition from breast milk to formula). Thus, Ba enrichment provides unambiguous evidence for postnatal feeding, as well as the beginning of supplementation; however, the transition from exclusive breastfeeding to formula intake may be obscured when breast milk remains the predominant dietary component after formula introduction. The extent of Ba/Ca increase at birth varies due to inter-individual differences in breast milk and formula Ba content. This is illustrated in Fig. 1f where the rise in Ba/Ca in response to breastfeeding is lower than in other individuals (Fig. 1d, e). Data on Ba/Ca values are given in Supplementary Table 1 and Supplementary Fig. 3.

Macaque permanent first molars also showed clear distinctions in Ba/Ca between pre- and postnatal regions, and close correspondence of postnatal changes in dental tissues and mother's milk (Supplementary Fig. 4). Although more diffuse owing to the nature of mineralization, Ba/Ca patterns in enamel correlated closely with dentine. Temporal mapping revealed Ba/Ca increases for the first 3–3.5 months of postnatal life (Fig. 2, Supplementary Figs 4–6 and Supplementary Table 2), followed by decreases that correlated with declines in suckling time and the initiation of solid food consumption. Moreover, Ba/Ca decreased more gradually during natural weaning than in

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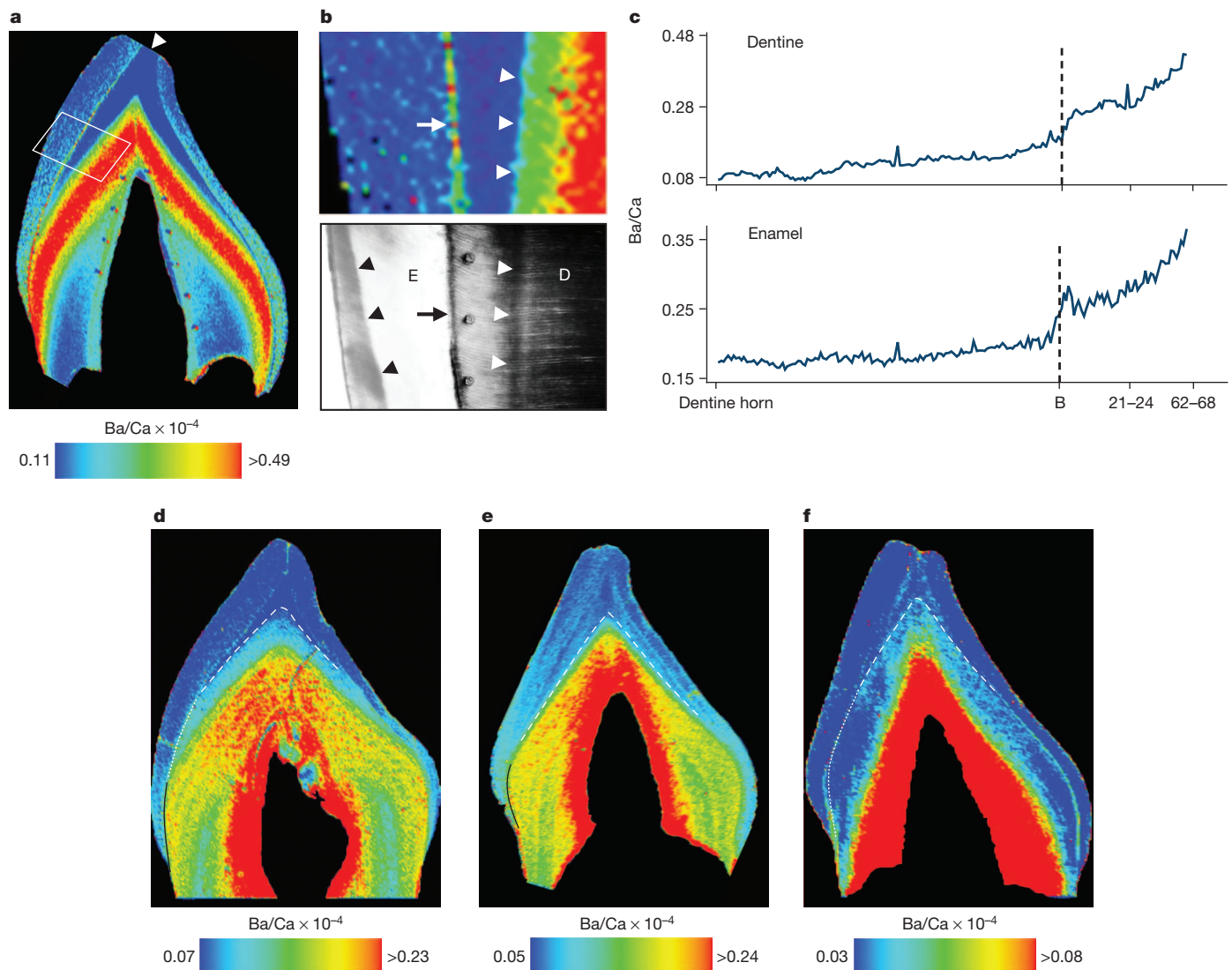


Figure 1 | Barium distribution in human deciduous teeth. **a**, Ba/Ca map of incisor. Dentine horn is indicated by an arrowhead. **b**, Area highlighted in **a** and polarized light micrograph. In dentine (D), Ba/Ca levels show a marked increase coinciding with the neonatal line (white arrowheads). The neonatal line in enamel (E) is indicated by black arrowheads and the enamel–dentine junction by arrows. **c**, Ba/Ca measured adjacent to the enamel–dentine junction from dentine horn to cervix of **a**, which rose at birth and with the introduction

of infant formula (21–24 days). The x axis shows days since birth (B). **d–f**, Three diet patterns: breastfeeding for 3 months (dotted white line) followed by exclusive formula feeding (solid black line) (**d**); formula introduced within 1 week of birth (solid black line) (**e**); and exclusive breastfeeding (dotted white line) (**f**). The neonatal line is indicated by a dashed white line. Intensity indices are $\text{Ba/Ca} \times 10^{-4}$. High Ba/Ca ratios adjacent to pulp (red zone) are in secondary dentine, a later-forming region not relevant to the current study (see ref. 12).

individuals who experienced truncated weaning periods (Fig. 2). In the most extreme case, an individual separated from its mother for several weeks at 166 days of age, precipitating cessation of milk synthesis and mammary gland involution, showed an abrupt Ba/Ca drop (Fig. 2c), which was independently estimated at 151–183 days of age.

Building upon our prospectively validated human and macaque results, we precisely documented diet transitions in a juvenile Neanderthal¹³. Barium is incorporated into the mineral phase (hydroxyapatite) during tooth calcification, which occurs rapidly after secretion in dentine, and more slowly and diffusely in enamel during maturation^{14,15}. Trace elements such as Ba are more resistant to post-mortem diagenetic alteration in enamel than in dentine, due in part to the greater original mineral content and lack of natural pores¹⁶. Thus, the distribution of Ba/Ca in well-preserved tooth enamel may yield direct information on early-life dietary transitions in fossil hominins.

Chemical and temporal mapping of Neanderthal first molar enamel (Fig. 3) revealed a transition pattern similar to the macaque that weaned abruptly. After approximately 13 days of prenatal enamel formation, Ba/Ca near the enamel–dentine junction increased and

remained elevated until approximately 227 days of age (~7.5 months), followed by intermediate values until 435 days of age (1.2 years). After this age Ba/Ca rapidly returned to prenatal levels for the final 1.15 years of crown formation. The Ba/Ca patterns in enamel were not observed in dentine due to diagenetic modification after death. However, diagenesis did not seem to have a significant influence on enamel, as concentrations of diagenetic indicators¹⁷ were low (Supplementary Table 3 and Supplementary Fig. 7). Furthermore, enamel Ba/Ca levels were similar to published values for other hominins^{11,18}, and Ba/Ca shifts were similar in form and timing between both mesial cusps, suggesting that the transition represents biogenic input rather than post-mortem modification (Supplementary Discussion). Although the subsurface occlusal and cervical enamel appears to show minor cracks that may lead to local modification¹⁷, most of the tooth crown is intact and naturally coloured. The *Sciadina* individual has also yielded mtDNA and enamel proteins^{19,20}, indicating that it is a well-preserved fossil.

Strontium/calcium ratios (Sr/Ca) in tooth enamel have been interpreted to reveal dietary transitions in baboons and humans^{9,21}. However, these events were inferred from species-typical norms or

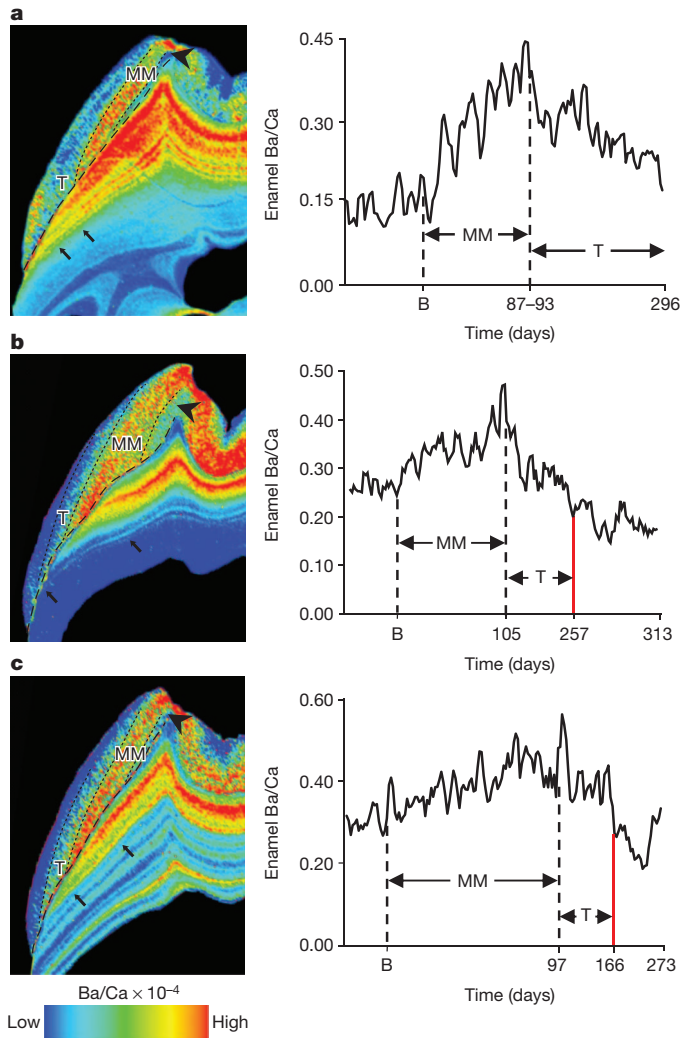


Figure 2 | Barium distribution reveals natural and truncated weaning. **a**, Macaque 515: natural weaning after 296 days. **b**, Macaque 152: weaned slightly early due to maternal separation at 257 days. **c**, Macaque 401: markedly truncated weaning owing to maternal separation at 166 days. This individual's weight fluctuated during the final 7 months of life due to illness; post-weaning enrichment may be owing to release from skeletal stores³⁰. Diet transitions: prenatal regions (arrowhead), exclusive mother's milk (MM), transitional (T) periods, and post-weaning regions delineated in enamel (dotted lines) and dentine (black arrows). The enamel–dentine junction is indicated with a dashed line. The y axis shows enamel Ba/Ca adjacent to the enamel–dentine junction. The x axis shows days since birth (B) and weaning (red line). Elemental maps of dentine and enamel were rendered on different scales to show Ba/Ca transitions clearly.

recalled retrospectively years after the event, which may be subject to significant recall bias²². In light of this, and concerns that Sr might be more susceptible to diagenetic alteration than Ba due to its higher diffusivity^{23,24}, a posthoc comparison of Sr/Ca and Ba/Ca was conducted. We found that the reconstruction of diet history from Sr/Ca mapping was impeded due to proportionately smaller changes in Sr levels across transitions and inconsistent patterns in human and macaque samples (Supplementary Figs 3, 8 and 9, Supplementary Tables 4 and 5, and Supplementary Discussion). Two distinct regions between birth and 1.2 years were observed in the Neanderthal tooth for Ba/Ca and Sr/Ca, representing exclusive breastfeeding and solid food supplementation, although this is less clear from Sr/Ca when compared to Ba/Ca (Supplementary Fig. 10). Thus, Ba/Ca provides greater resolution of dietary transitions than Sr/Ca in extant and fossil material. Nonetheless, measurements of Sr isotopes in enamel have yielded useful data on diet and migration in early hominins¹⁸.

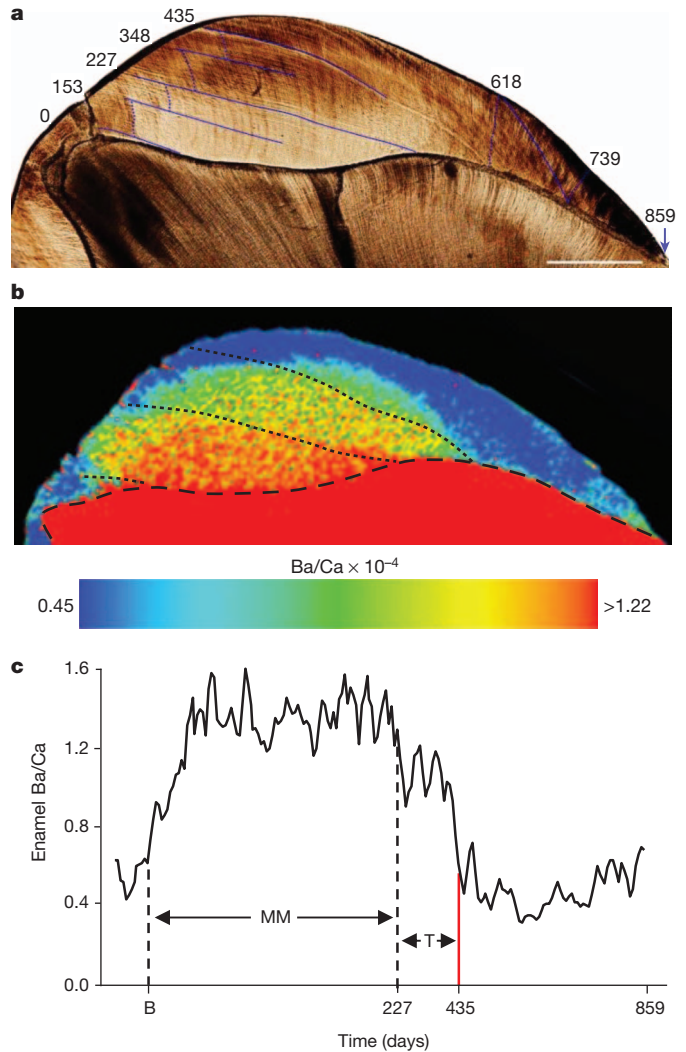


Figure 3 | Dietary transitions in a Neanderthal permanent first molar. **a**, Developmental time (in days from birth) of stress lines in enamel (dark blue lines) was determined from daily growth increments (following dotted blue lines). Scale bar, 1 mm. **b**, Ba/Ca map shows marked variations in enamel at birth, 227 and 435 days, which resemble human and macaque transitions from exclusive maternal milk (MM) consumption to supplementation. **c**, Ba/Ca in enamel adjacent to the enamel–dentine junction. The x axis shows days from birth (B) to proposed exclusive MM, transitional diet (T) periods and hypothesized weaning event (red line). Elevated Ba/Ca levels at the very beginning and end of crown formation are probably due to subtle diagenetic modification¹⁷.

We have shown a direct correlation between Ba/Ca distributions in human deciduous teeth and breastfeeding data collected prospectively, thereby avoiding recall bias. In the macaques, patterns of suckling behaviour and Ba concentration in mother's milk are consistent with Ba/Ca in dental tissues, which consistently show a decrease in Ba/Ca from the onset of supplementation. Taken collectively, these results demonstrate that Ba/Ca in teeth effectively reflect Ba intake via mother's milk, and can be used to document developmental transitions in future studies of wild primate skeletal material, and for assessments of human health outcomes.

In the Scladina Neanderthal, the protracted weaning process typical in primates was interrupted by unknown cause(s), precipitating abrupt cessation of suckling. The period of exclusive breastfeeding in this Neanderthal is consistent with other hominoids; human hunter-gatherers and wild chimpanzees also begin to supplement milk with solid food by around 6 months of age^{5,25}. Humans and chimpanzees may wean offspring as early as 1.0 and 4.2 years, respectively, without

serious health effects, but average 2.3–2.6 years⁵ and 5.3 years²⁵. When applied to additional samples, our approach will allow the evaluation of hypotheses that Neanderthal young routinely weaned at later ages than Upper Palaeolithic hominins²⁶, or possessed faster life histories than modern humans¹³, which have important implications for models of hominin population growth and species replacement.

METHODS SUMMARY

Human teeth were supplied from the Center for the Health Assessment of Mothers and Children of Salinas study, Monterey County, California, USA²⁷. Pregnant women were recruited before 20 weeks gestation, and data on breastfeeding and use of infant formulas were prospectively collected. From the 7-year assessment onwards, mothers were asked to bring in a tooth the child had shed, which was prepared according to standard histological techniques. The neonatal line was used to identify pre- and postnatal developmental periods. Prominent long-period incremental lines were mapped, and daily growth cross-striations in enamel were measured to determine the average daily enamel secretion rate. Macaque samples were obtained from two mother–infant dyads and two additional juveniles at the California National Primate Research Center (CNPRC), UC Davis, California, USA. Mothers and infants were captured for milk collection and morphometric measurements three times during lactation. Methods for rhesus macaque milk collection are described elsewhere⁸. In the week before milk collection, observations of infant suckling behaviour were recorded²⁸. Dentitions were collected opportunistically during animal necropsy in conjunction with the CNPRC Biological Specimens Program. First molars were dissected out after fixation, and histological sections were prepared and analysed following established protocols¹³. The Sciadina Neanderthal upper first maxillary molar had been previously sectioned and temporally mapped¹³. Laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) was used for elemental analysis of all samples according to published protocols²⁹. Instrument parameters were selected to generate images with pixel sizes of approximately 900 μm^2 . Reported element ratios ($\text{Ba}/\text{Ca} \times 10^{-4}$ and $\text{Sr}/\text{Ca} \times 10^{-3}$) were calculated from concentrations determined using ⁴³Ca, ⁸⁸Sr and ¹³⁸Ba with standard NIST 1486 bone meal. Other elements were quantified against NIST 612 as a standard. Changes in Ba/Ca were assigned ages by overlaying photomicrographs from histological temporal maps, which were registered along the enamel–dentine junction.

Full Methods and any associated references are available in the online version of the paper.

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Supplementary Information is available in the online version of the paper.

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Author Contributions C.A., T.M.S. and M.A. designed the study, undertook the elemental and histological analysis, and wrote the manuscript. A.B. and B.E. designed and analysed the human study. K.H. designed the macaque lactation study and collected samples. R.J.-B. analysed the Payre Neanderthal tooth in the Supplementary Information and assessed diagenetic alteration. C.A., D.J.H., D.B. and P.D. undertook elemental imaging of tooth samples. All authors contributed to the interpretation of the results, in addition to editing the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to M.A. (marora@hsph.harvard.edu).

METHODS

Human study participants. We used teeth from children enrolled in the Center for the Health Assessment of Mothers and Children of Salinas (CHAMACOS) study in Monterey County, California^{27,31}. Pregnant women in the CHAMACOS cohort were recruited before 20 weeks gestation, and data on breastfeeding and infant formulas used were prospectively collected. Interviews were conducted with participants twice during pregnancy (at the end of the first and second trimesters), immediately postpartum, and when children were approximately 6, 12, 24 and 42 months old. Interviews were conducted in person, either at the study office or in a modified recreational vehicle that was used as a mobile office at the participant's home. All questionnaires were administered in English or Spanish by trained bicultural interviewers, with most interviews (94%) conducted in Spanish. Study instruments were developed in English, translated, and validated by Mexican-American immigrant staff members familiar with the language of the community and of southern Mexico from where many participants migrated.

At the second pregnancy interview (mean = 27 weeks gestation), the participant was asked if she intended to breastfeed her child. At each of the postpartum interviews she was asked if she was currently breastfeeding. At the interview when the mother first answered that she was no longer breastfeeding, she was then asked the child's age when she had completely stopped breastfeeding and the reasons for stopping. Additionally, at the 6-month interview, the mother was asked if her child was receiving formula, and if so, at what age formula had been introduced. At the 12-month interview, she was asked at what age formula, solid foods and cow's milk were each introduced. Duration of exclusive breastfeeding was defined as the period between birth and the age when food or liquid other than breast milk or water was first given. All procedures were reviewed by the University of California at Berkeley Committee for the Protection of Human Subjects. Written informed consent was obtained from parents of all participating children and oral assent was obtained from 7 year olds.

From the 7-year assessment onwards, mothers were asked to bring in a tooth the child had shed. We randomly selected deciduous teeth that were free of obvious defects (caries, hypoplasias, fluorosis, cracks, extensive attrition) from 25 children who fell into one of three categories: exclusively breastfed from birth; initially breastfed with formula introduced within 1–2 months of birth; or exclusively formula fed soon after birth. We prepared ~100–150- μm -thick sections in an axial labio-lingual plane following established methods. Developmental times were assigned to marked shifts in Ba/Ca in tooth sections with histological analyses. We photographed the enamel–dentine junction and the neonatal line in enamel and dentine. We overlaid these photomicrographs on our elemental maps to distinguish pre- and postnatal regions (Fig. 1). In teeth of children whose mothers introduced formula within 1–2 months of birth, we noticed clear high Ba/Ca bands in the postnatally formed dentine some distance from the neonatal line. To assign a developmental time to these zones, we used polarized light microscopy to visualize prominent long-period incremental lines and cross-striations (daily growth increments) in enamel, and measured the distance between consecutive cross-striations to determine the average daily enamel secretion rate. Developmental times were then assigned to different points in enamel and dentine along the enamel–dentine junction.

Macaques. Data and samples were obtained from two mother–infant dyads and two additional juveniles at the California National Primate Research Center, UC

Davis, California. All subjects were housed in large, intact social groups in outdoor corrals (0.2 ha). Mothers received a nutritionally complete commercial diet (Outdoor Monkey Lab Diet, PMI Nutrition, Intl) twice daily. Subjects were part of a larger, on-going study on lactation and infant development⁸. Three times during lactation, at infant age 1, 3–4 and 5–6 months, mothers and infants were relocated for milk collection and morphometric measurements as described in detail elsewhere⁸. In the week previous to milk collection, trained technicians conducted four 10-min focal observations between 8:30 and 12:30 and recorded duration of infant suckling behaviour²⁸. All experimental procedures were conducted in accordance with ethical guidelines and with UC Davis Institutional Animal Care and Use Committee approval. Denticions were collected opportunistically during animal necropsy as part of the CNPRC Biological Specimens Program.

Neanderthal sample. The Scladina Neanderthal upper first maxillary molar was sectioned and temporally mapped for a previous developmental study that established this individual died at approximately 8 years of age¹³.

Ba measurements in teeth using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). We used a New Wave Research UP-213 laser ablation system equipped with a Nd:YAG laser emitting a nanosecond laser pulse in the fifth harmonic with a wavelength of 213 nm. The laser was connected to an Agilent Technologies 7500cs ICP-MS by Tygon tubing. Details of our analytical methods have been published previously²⁹. In brief, the laser beam was rastered along the sample surface in a straight line. A laser spot size of 30 μm , laser scan speed of 60 $\mu\text{m s}^{-1}$ and ICP-MS total integration time of 0.50 s produced data points that corresponded to a pixel size³² of approximately 900 μm^2 . Reported element ratios ($\text{Ba/Ca} \times 10^{-4}$ and $\text{Sr/Ca} \times 10^{-3}$) were calculated from concentrations determined using ⁴³Ca, ⁸⁸Sr and ¹³⁸Ba isotopes and NIST 1486 bone meal as a standard. NIST 1486 was not certified for Ba so an average concentration calculated from determinations in two other studies^{33,34} was used. Diagenetic indicators were quantified using NIST 612 glass standard. Each line of ablation produced a single data file in comma separated value (.csv) format. Data were processed using Interactive Spectral Imaging Data Analysis Software (ISIDAS), a custom-built software tool written using Python programming language. ISIDAS reduced all .csv files into a single, exportable visualization toolkit (.vtk) file format. Images were produced by exporting .vtk files into MayaVi2 (Enthought Inc.), an open source data visualization application. Colour scales were applied using the linear blue–red LUT. Image backgrounds were converted to black (absent from the colour intensity scale) to clarify sample boundaries from the substrate. Elemental maps were rotated and black boarders added where needed to align rectangular figure panels.

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