Peer Community Journal

Section: Archaeology

Research article

Published
2025-12-04

Cite as
Samuel Bédécarrats, Mélie Le Roy, Kerry L. Sayle, Frédérique Blaizot, Maëlle Couvrat, Yves Gleize, Guillaume Leduc, Stéphane Rottier and Gwenaëlle Goude (2025) *Isobiography of the first farmers: effects of age-estimating referential and statistical models on reconstructing infant life from dentinal isotopic sequences*, Peer Community Journal, 5: e135.

Correspondence
bedecarrats.samuel@gmail.com

Peer-review
Peer reviewed and recommended by PCI Archaeology,
https://doi.org/10.24072/pci.archaeo.100609

Isobiography of the first farmers: effects of age-estimating referential and statistical models on reconstructing infant life from dentinal isotopic sequences

Samuel Bédécarrats[#,1], Mélie Le Roy[#,2], Kerry L. Sayle[3], Frédérique Blaizot[4], Maëlle Couvrat[1], Yves Gleize[5,6], Guillaume Leduc[7], Stéphane Rottier[6], and Gwenaëlle Goude[#,1]

Volume **5** (2025), article e135

https://doi.org/10.24072/pcjournal.657

Abstract

The use of isotopic sequence allowing a longitudinal life tracking of an individual (isobiography), by taking a series of isotope measurements on dentine sections and estimating the age of the individual at their formation, provides a means of tracing dietary and environmental variations during childhood. This approach is based on the use of standards for estimating the age at which teeth are formed. By using a dual mathematical model, linear and a generalised additive model, and by testing two standards commonly used in biological anthropology to estimate dental age, we have characterised the isobiography of 4 Neolithic individuals from France. Our study shows the importance of the choice of mathematical model and standard in age estimates. Depending on the choices made, there can be gaps of several years between the estimates, underscoring the difficulty and precautions that need to be taken when making inferences on social ages. The statistical processing protocol developed can be re-used or adapted for new studies.

[1]CNRS, Aix Marseille Université, Ministère de la Culture, INRAP, LAMPEA, Aix-en-Provence, France, [2]Department of Archaeology And Anthropology, Faculty of Science and Technology, Bournemouth University, Poole, UK, [3]SUERC, University of Glasgow, Scottish Enterprise Technology Park, East Kilbride, UK, [4]UMR 8164 HALMA, CNRS, Université de Lille, Inrap, Lille, France, [5]Inrap Nouvelle-Aquitaine et Outre-mer, Bègles, France, [6]UMR 5199 PACEA, CNRS, Université de Bordeaux, Ministère de la culture, Bordeaux, France, [7]Aix Marseille Université, CNRS, IRD, CdF, INRAE, CEREGE, Aix en Provence, France, [#]Equal contribution

Peer Community Journal is a member of the Centre Mersenne for Open Scientific Publishing
http://www.centre-mersenne.org/

e-ISSN 2804-3871

Introduction

Aims of the study

In bioarcheology, the study of childhood through isotopic sequence or dataset allowing a longitudinal life tracking of an individual (frequently referred as “isobiography”) is a valuable source of information. However, such approaches face a number of limitations resulting from the methods used to align data with numerical ages. In this study, we propose to explore the effects of several methodological decisions regarding realignment: the choice of a dental maturation standard and the modelling method. We will discuss the consequences of these choices using the example of Neolithic individuals.

Childhood in prehistory

Since the late 1980s (Lillehammer, 1989), children and childhood have gradually become a subject of study in their own right in archaeology (Mays et al., 2017). Recent research has shown the importance of considering this part of the population in order to understand past societies holistically (e.g. Murphy, 2017; Crawford et al., 2018; Le Roy, 2022). Indeed, children are the members of society who ensure the perpetuation of culture and the survival of the populations to which they belong. Defining the different stages leading to adulthood is therefore essential for a better understanding of the society under study. These stages are determined not only by biology (e.g. puberty) but also by context, whether environmental (e.g. growth) or cultural (e.g. weaning). Moreover, it is the latter that informs social age classes marked by "rites de passage" (Van Gennep, 1901), which allow us to assess the social consideration (as well as its evolution) of children within the population (Le Roy, 2015). To date, few studies have focused on this aspect of ancient societies, with the few available focusing mainly on burial practices (e.g. Tillier, 1995; Dedet, 2008; Murphy & Le Roy, 2017; Le Roy, 2022), diet, especially around the weaning age (e.g. Herrscher & Séguy, 2019), or childhood diseases (e.g. Lewis, 2018). However, children are an integral part of all daily activities and social behaviours in the communities studied. In Gurgy Les Noisats (Yonne, France) during the Middle Neolithic, female children were no longer present in the local group after the age of seven, and women who gave birth were all from outside the local group (Rivollat et al., 2023). The variations in isotopes observed during adolescence are due to a combination of hormonal factors (Kurle et al., 2014; Feuillâtre et al., 2022), changes in physiological needs (Das et al., 2017), diet (Griffith et al., 2025) and status that are frequent at these ages (Lew-Levy et al., 2017). In the case of Gurgy, patrilocality seems to be the most important factor in explaining the constant difference between girls and boys in adolescence. It is therefore reasonable to assume that young girls move to other contemporary groups around the age of puberty in order to diversify the gene pool. Similarly, isotopic analyses of this population have revealed a change in diet at certain ages during childhood (between 7 and 8 years, then around 13 years, Rey et al., 2021). These pivotal ages are identical to those at which changes in burial practices are observed (Le Roy et al., 2018).

Characterising life-history variation using isobiography

The combination of longitudinal isotope data sequences, biological, osteobiographical and archaeological data (isobiography; ie. isotopic sequence or dataset allowing a longitudinal life tracking of an individual) offers the possibility of tracing the different events in an individual's life. While the study of sequential isotopic compositions on tooth enamel is well known in palaeoanthropological (review in Smith, 2013) and bioarchaeological (e.g. Zazzo et al., 2010) research, the use of dentine sequences has only recently been invested in anthropology. Recently developed tracking changes in the isotopic composition of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) values contained in the collagen of dental tissue (dentine, e.g. Eerkens et al., 2011; Beaumont et al., 2013), whose age of formation can be estimated, provides a unique insight into the life history of individuals. This intra-individual longitudinal tracking allows (with greater precision than bone;

Beaumont et al., 2018) physiological, economic and cultural changes, such as estimating the duration of breastfeeding, weaning (e.g. Eerkens et al., 2011) or feeding during childhood and adolescence. This high-resolution monitoring has documented physiological stress with a temporality useful for palaeosocial interpretations, such as the effects of famine in Ireland (Beaumont & Montgomery, 2016) or environmental changes between boys and girls during prehistoric adolescence (Rey et al., 2021). Technical advances in the sensitivity of isotope ratio mass spectrometers in recent years have greatly facilitated the use of this type of study, despite its invasive nature and impact on heritage. For example, it is possible to reduce sample sizes to increase the resolution of isotopic tracing, or to perform other analyses, such as measuring the isotopic composition of sulfur ($\delta^{34}S$), on the same sample (Sayle et al., 2019). The integration of $\delta^{34}S$ values makes it possible to differentiate the influence of mobilities in relation to, for example, physiological responses to stress, growth or starvation (Goude et al., 2020a). Longitudinal monitoring of the three isotopic compositions mentioned allowing us a follow-up with a different interpretative perspective with regards to the consumption of protein resources (e.g. breast milk and weaning food), in relation to the supply environment (e.g. dietary changes during life, Beaumont & Montgomery, 2016; differences in resources produced, Goude et al., 2020b) and physiological responses (growth peaks, stress and changes in protein catabolism and gluconeogenesis; e.g. Hobson et al., 1993; Mekota et al., 2006; Neuberger et al., 2013). Also, as mentioned by Eerkens et al. (2011), secondary dentine, which is present in smaller amounts, can now be used to extend the individual longitudinal record. For example, Bernardini et al. (2023) have constructed an isobiography of a medieval woman in central Italy from which it is possible to trace the duration of weaning, mobility during infancy, care during deteriorating health and dietary status until death at around age 50.

The construction of an isobiography requires two main parameters: the ability to take successive and numerous samples along the tooth to obtain sufficient resolution of information, and the ability to provide an age estimate with the smallest possible margin of error for each section of dentine sampled. Czermak et al. (2020) propose to combine a reduced sample size (by biopsy punch) with an age adjustment that follows a specific growth rate for each part of the tooth (crown, crown-root junction - CRJ, root, apex). Other authors, such as Scharlotta et al. (2018), include a reflection on the reference frames to be used depending on the origin of the archaeological populations studied. By comparing different age alignment methods and tracing the isotopic sequences of three permanent molars with partially overlapping and successive growth (first molar - M1, second molar - M2 and third molar - M3), the authors show that there are dental growth discrepancies between Siberian Neolithic children and modern populations, and that a growth reference made from populations whose genetic heritage is closest to the archaeological individuals can partially mitigate age estimation errors. Furthermore, it has been shown that the rhythmicity of dental growth in humans is influenced by environmental variables that affect life history (life history variables; Ramirez Rozzi, 2016). Furthermore, the choice of dental maturation standards has an impact on the social inferences made: each standard will produce a different result for estimating the age of formation of dentine sections. The use of different standards makes it impossible to make inter-data comparisons. Therefore, it is crucial to find the right criteria when choosing an age estimation method by taking into account both the constraints linked to the material and to the use and comparison of previously obtained data.

This problem may be exacerbated in a context where many efforts are being made to provide (1) databases accessible to all (such as Amalthea, accessible in the Pandora consortium; Cocozza & Fernandes, 2021) and (2) statistical or machine learning tools to identify chronologies of behavioural change (e.g. estimation of age at weaning with the WEAN software, (Ganiatsou et al., 2023a; Ganiatsou et al., 2023b). Finally, this finding also raises questions about the preservation of bioarchaeological remains and the assessment of the risk/reward trade-off between sampling, heritage impact and scientific contributions. Nevertheless, isotopic and biomolecular sequence data from human remains are a unique source of information and have made a major contribution to understanding the geographical and historical variability of behaviours that raise questions about our present and future societies. In the context of such studies, it is necessary to establish a methodology for estimating age at death that is as reliable and accurate as possible in order to monitor the ages at which social change occurs.

Estimating age from tooth development

Teeth develop from a proliferation of epithelial cells that form a germ. Around the germ, ameloblasts deposit a matrix that mineralises to form enamel (Hillson, 2005, pp. 207–211). Odontoblasts deposit a dentine matrix to support dentine mineralisation. These two tissues, enamel and dentine, develop in successive layers following a relatively short chronology that is consistent between individuals. Observation of a stage of dental development is therefore a reliable method of determining an individual's age (Smith, 1991). Longitudinal biochemical analyses of dentinal sections are based on these growth rhythms and propose a correspondence between the location of the sections analysed and the stages of dental development. Numerous references have been published on the stages of mineralisation. They are mainly based on radiographic observations of current populations (Table 1).

Table 1 - Dental maturation benchmarks and eruption atlases commonly used to estimate ages at death in biological anthropology. Data compilation 1: the Atlas established by Gustafson and Koch (1974) is a compilation of data obtained by (Röse, 1909; Logan & Kronfeld, 1933; Klein et al., 1937; Cohen, 1940; Schour et al., 1941; Robinow et al., 1942; Kranz, 1946; Dahlberg & Bernhard Maunsbach, 1948; Stones et al., 1951; Clements et al., 1953; Gödény, 1955; Orban, 1957; Tegzes, 1959; Nolla, 1960; Fanning, 1961; Sjöberg, 1961; Carr, 1962; Moyers, 1963; Lysell et al., 1964; Haavikko, 1970); Data compilation 2: the Atlas established by Ubelaker (1978) is a compilation of data obtained by (Robinow et al., 1942; Steggerda & Hill, 1942; Meredith, 1946; Hurme, 1948; Demisch & Wartmann, 1956; Dahlberg & Menegaz-Bock, 1958; Kraus, 1959; Nolla, 1960; Moorrees et al., 1963a; Moorrees, et al., 1963b; Gilster et al., 1964; Moorrees, 1965; Christensen & Kraus, 1965; Coughlin & Christensen, 1966; Banerjee & Mukherjee, 1967; Lunt & Law, 1974; Anderson et al., 1976) NS1 According to (Schour et al., 1941), around 1000 teeth.

Type	Reference	Country	N Boys	N Girls	N unknown sex	Age range (years)
Referential maturation	(Anderson et al., 1976)	Canada	121	111	0	[3.5-18]
Referential maturation	(Demirjian et al., 1973)	Canada	1446	1482	0	[2-20]
Referential maturation	(Demirjian & Levesque, 1980)	Canada	2705	1732	0	[2-19]
Referential maturation	(Haavikko, 1970)	Finland	615	547	0	[2-21]
Referential maturation	(Hägg & Taranger, 1985)	Sweden	122	90	0	[0-18]
Referential maturation	(Liversidge & Speechly, 2001)	United Kingdom	263	258	0	[4-9]
Referential maturation	(Moorrees et al., 1963a)	United States of America	136	110	0	[0-15]
Referential maturation	(Moorrees et al., 1963b)	United States of America	48	51	0	[0-25]
Referential maturation	(Nolla, 1960)	United States of America	25	25	0	[2-23]
Referential maturation	Poolsanguan mentioned in (Liversidge, 2003)	United Kingdom	279	255	0	[5-15]
Referential maturation	(Simpson & Kunos, 1998)	United States of America	152	151	0	[2.2-18]
Referential maturation	(Willems et al., 2001)	Belgium	1460	1418	0	[2-18]
Referential maturation	(Zhao et al., 1990)	China	465	438	0	[3-16]
Atlas	(AlQahtani et al., 2010)	United Kingdom, Bangladesh	336	355	13	[-0,25-24]
Atlas	(Gustafson & Koch, 1974)	data compilation 1	data compilation 1	data compilation 1	data compilation 1	[2-16]
Atlas	(Kahl & Schwarze, 1988)	Germany	535	458	0	[5-24]
Atlas	(Schour et al., 1941)	United States of America	NS1	NS1	NS1	[-0,42-35]
Atlas	(Ubelaker, 1978)	data compilation 2	data compilation 2	data compilation 2	data compilation 2	[-0,42-35]

Another approach commonly used to estimate an individual's age from dental maturation is the use of atlases (Schour et al., 1941; Gustafson & Koch, 1974; Ubelaker, 1978; Kahl & Schwarze, 1988; AlQahtani et al., 2010). These graphically depict the development of the dentition by age class. Although commonly used, these atlases are difficult to apply to archaeological material as they require exhaustive observation of the dentition and do not allow for a per-tooth estimate (Cunningham et al., 2016). Furthermore, they do not estimate a numerical age, but propose an age class, which limits the statistical analysis of the results. Nevertheless, these atlases are favoured for the study of large series due to their ease of use (Arumugam & Doggalli, 2020).

Methodological challenges and new data on the French Neolithic

One of the objectives of the international WomenSOFar project (ANR-21-CE03-0008) is to identify the variability of parental and alloparental care behaviours within early Neolithic agropastoral societies (5th-4th millennium BC), by tracking breastfeeding and weaning periods. These data are then be compared with the geographical origins of human groups and sampling choices (e.g. maxillary versus mandibular) to understand the possible impact of environmental differences on these life trajectories and potentially on health status and growth. We propose first to evaluate the statistical processing of our sequential isotopic data on a limited number of individuals from the same geographical area, and then to open the debate on the methodological orientations to be favoured when interpreting data from individuals with different genetic and ecological origins.

Material and Methods

Archaeological context

The site of Le Brézet is located on the western edge of the Limagne Tertiary collapse trough in the Clermont-Ferrand basin (Puy-de-Dôme, France). The geological substratum, which consists of detrital lacustrine deposits and then carbonates, is overlain by marshy levels dating to around 11460 BP, which in turn are overlain by volcanic fallout. The latter disrupted hydrographic networks and contributed to the formation of marshy areas that persisted into modern times. It is in this environment that human societies have inhabited the area since the early Neolithic period. Apart from traces of intensive deforestation and the presence of layers of pottery, lithics and fauna found in these silty-sandy layers, with some objects suggesting deliberate deposition, this occupation did not reveal any settlement structures. The Neolithic burials can be divided into two groups (Blaizot, 2005). The first consists of 11 grouped individual burials dated by two radiocarbon dates to the Early Middle Neolithic (two radiocarbon dates: 4455-4334 BCE and 4539-4359 BCE, details available in Blaizot, 2005). These burials form part of a large area dedicated to the burial of the deceased, including those at Pontcharaud, 250 m S-E of Le Brézet (Loison et al., 1991). Individuals were laid on their right or left side, with the limbs bent, without any relation to sex or age at death. The swampy nature of the site had an impact on the taphonomy of the skeletons, with small pieces of bone dispersed by the movement of the water table. The second group consists of a child burial in a silo-like pit, from which the head bones were removed and then replaced in an upper sequence of the pit fill by the craniofacial blocks of two other immature individuals (Blaizot & Vernet, 2004). A recent revision of the deposit allows us to date this assemblage to 2550-2450 BCE (Letterlé, 2021, pp. 24–25).

Samples and isotope analysis

The material studied for this exploratory work consists of four molars from four different individuals from Le Brézet site dating to the Middle Neolithic. Their ages at death were estimated using methods based on dental (Schour et al., 1941; Moorrees et al., 1963a; Moorrees et al., 1963b) and skeletal maturation (Sundick, 1978; Birkner, 1980) and senescence (Masset, 1982; Lovejoy, 1985; Brooks & Suchey, 1990; Schmitt, 2005). Their sexes were estimated using methods based on pelvic sexual dimorphism (Brůžek, 1991, 1996; Murail et al., 2005). Three definitive second molars (left and right mandibular M2 and right maxillary M2) and one first molar (right maxillary M1) were documented (photographs, 3D reconstruction using an Artec Spider surface scanner), sampled and prepared in the laboratory for isotopic analysis of carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$) and sulfur ($\delta^{34}S$) along the tooth from the top of the crown to the end of the root (cf. example of technical protocol in Goude et al., 2020a; Figure 1, Table 2 and SI).

Teeth were selected in order to respect the best preservation conditions of Le Brezet osteological collection (unworn, without visible taphonomic damages or pathology). The three second molar (M2) have a growth period allowing to address different periods of life that are comparable between individuals and that can cover changes in life history, also known as social ages (cf. Rey et al. 2021). The first molar (M1) provides an initial glimpse into a life history more closely linked to the maternal-infant nexus. A sagittal section of each tooth was performed with a precision saw in order to obtain a complete section from the cusp to root (Figure 1). The section is smoothly abraded with aluminum oxide by a sandblaster in order to remove the external surface of the enamel and the root. The section is then demineralized in HCl (0.05M) at 4°C for several days and rinsed with distilled water after demineralization was completed. The section is then soaked in NaOH (0.125M) for 1h to remove potential remaining contaminants and rinsed. Transverse sections of dentine were realized with a sterilized scalpel, with a thickness of one millimeter when possible, or more when dentine was too fragile to allow for a thinner section. Each section is frozen and freeze-dried for 24h and then weight in tin caps (0.8 to 1.5 mg) for the IRMS analyses.

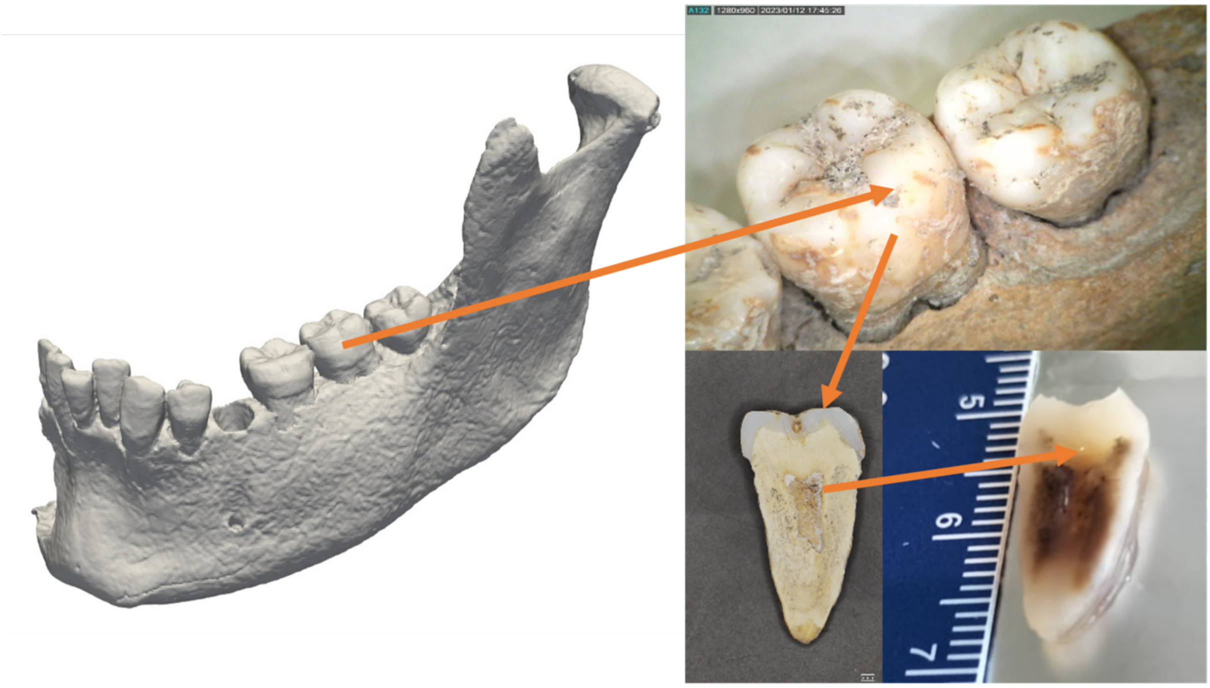

Figure 1 - Example of archiving and sampling protocol 3D surface scanner (Artec Spider; file available in SI), digital microscope photo (Hirox) of targeted second molar, before and after demineralization photo of analyzed tooth section.

Table 2 - Individual biological data and descriptions of sampled teeth

Tooth	Individual ID	Total length of the tooth dentine	Tooth growth stage	Nb of dentine section	Age at death (est. from bone study)	Sex	Complementary information
M2 mandibular left	Brézet C324 9/1	19 mm	Apex open	15	15-19 yrs old	F	
M2 mandibular Right	Brézet C314 Sep 8	17.35 mm	Apex closed	10	Aged adult	F	
M2 maxillar Right	Brézet C313 sep 4	20 mm	Apex closed	14	15-19 yrs old	M?	Infectious disease
M1 maxillar Right	Brézet sep 2	19 mm	R3/4 - Rc	14	5-10 yrs old	Undet	

Stable carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), and sulfur ($\delta^{34}S$) isotopic compositions were determined on a Delta V Advantage continuous-flow isotope ratio mass spectrometer coupled via a ConfloIV to an IsoLink elemental analyser (Thermo Scientific, Bremen) at SUERC, East Kilbride as described in (Sayle et al., 2019).

Samples were combusted in the presence of oxygen in a single reactor containing tungstic oxide and copper wires at 1020°C to produce N2, CO2 and SO2. A magnesium perchlorate trap was used to eliminate water produced during the combustion process, and the gases were separated in a GC column heated between 70°C and 240°C. Helium was used as a carrier gas throughout the procedure. N2, CO2, and SO2 entered the mass spectrometer via an open split arrangement within the ConfloIV and were analysed against their corresponding reference gases.

The International Atomic Energy Agency (IAEA) reference materials USGS40 (L-glutamic acid, $\delta^{13}C_{VPDB}$ = –26.39 ± 0.04‰, $\delta^{15}N_{AIR}$ = –4.52 ± 0.06‰) and USGS41a (L-glutamic acid, $\delta^{13}C_{VPDB}$ = 36.55 ± 0.08‰, $\delta^{15}N_{AIR}$ = 47.55 ± 0.15‰) were used to normalise $\delta^{13}C$ and $\delta^{15}N$ values. An in-house standard (5-SAAG, $\delta^{34}S_{VCTD}$ = –12.86 ± 0.20‰) that is calibrated to the International Atomic Energy Agency (IAEA) reference materials IAEA-S-2 (silver sulfide, $\delta^{34}S_{VCTD}$ = 22.62 ± 0.08‰) and IAEA-S-3 (silver sulfide, $\delta^{34}S_{VCTD}$ = –32.49 ± 0.08‰) and the marine collagen USGS88 ($\delta^{34}S_{VCTD}$ = 17.10 ± 0.44‰) were used to normalise $\delta^{34}S$ values. Results are reported as per mil (‰) relative to the internationally accepted standards VPDB, AIR and VCDT.

Normalisation was checked using the Elemental Microanalysis standards B2219 (Coldwater fish gelatin: $\delta^{13}C_{VPDB}$ = –16.33 ± 0.10‰, $\delta^{15}N_{AIR}$ = 14.71 ± 0.14‰, and $\delta^{34}S_{VCTD}$ = 17.05 ± 0.07‰), B2222 (Bovine gelatin: $\delta^{13}C_{VPDB}$ = –11.11 ± 0.091‰, $\delta^{15}N_{AIR}$ = 7.54 ± 0.12‰, and $\delta^{34}S_{VCTD}$ = 6.79 ± 0.08‰) and B2215 (fish gelatin: $\delta^{13}C_{VPDB}$ = –22.92 ± 0.10‰, $\delta^{15}N_{AIR}$ = 4.26 ± 0.12‰, and $\delta^{34}S_{VCTD}$ = 1.21 ± 0.24‰).

On the basis of the check and calibration standards, measurement precision (the pooled standard deviation of the check and calibration standards) was ±0.08‰ for $\delta^{13}C$ (df=41), ±0.49‰ for $\delta^{15}N$ (df=41), and ±0.32‰ for $\delta^{34}S$ (df=29).

Measurement precision specific to duplicate samples (the pooled standard deviation of all samples analysed in duplicate) was ±0.03‰ for $\delta^{13}C$ and ±0.26‰ for $\delta^{15}N$ (df=12).

Precision (u(Rw)) was determined to be ±0.09‰ for $\delta^{13}C$ and ±0.52‰ for $\delta^{15}N$ on the basis of repeated measurements of calibration standards, check standards, and sample replicates.

Measurement accuracy or systematic error (u(bias)) was evaluated by comparing the known and measured $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values for B2219, B2222, and B2215, and was determined to be ±0.14‰ for $\delta^{13}C$, ±0.25‰ for $\delta^{15}N$, and ±0.55‰ for $\delta^{34}S$.

Choice of dental maturity reference systems

The two reference systems proposed by Coenraad F. A. Moorrees and colleagues (Moorrees et al., 1963a; Moorrees et al., 1963b) are among the most widely used for dental age estimation in archaeology (Cunningham et al., 2016, p. 165) due to their reliability (Buckberry, 2018, p. 59) and because this is one of the few longitudinal studies conducted. The raw data were published by (Harris, 2018; Harris & Buck, 2018), which facilitated their statistical processing. These references were established for three decidual teeth (lower C, M1 and M2) from longitudinal radiographs of 136 boys and 110 girls stored at the Fels Research Institute (Yellow Springs, Ohio, USA). For permanent teeth, radiographs of the entire mandibular dentition and maxillary incisors of 51 girls and 48 boys from Boston (Massachusetts, USA) were used as a reference. The atlas developed by Sakher J. AlQahtani and colleagues (AlQahtani et al., 2010) is the most commonly used reference for longitudinal isotopic studies (e.g. Beaumont & Montgomery, 2015; Fernández-Crespo et al., 2018; Van Der Haas et al., 2018; Scharlotta et al., 2018; Crowder et al., 2019; Czermak et al., 2020) due to its reliability and the fact that it documents the entire dentition over a large number of mineralisation stages (García-Mancuso & Salceda, 2014). This atlas was compiled from the skeletal remains of 91 boys, 72 girls and 12 individuals of undetermined sex, and the radiographs of 264 girls and 264 boys. For our study, we developed a statistical processing protocol to automate the alignment of dentine sections to these two reference frames. We used raw data from (Moorrees et al., 1963a; Moorrees et al., 1963b) formatted in (Harris, 2018; Harris & Buck, 2018) and (AlQahtani et al., 2010). These references are hereafter referred to as 'Moorrees et al.' and 'AlQahtani et al.'.

Modelling tooth growth and estimating the age of formation of dentine sections

Data processing involved three main stages: alignment of the individual's sections to the reference frame, modelling of the dental maturation curve on the reference frame, and imputation of age values corresponding to the sections of the individual studied. All these operations were carried out using R software, version 4.3.0 (R core Team, 2024), and the complete script is available in SI. The sections are transformed into numerical sequences ranging from 0 to 1 by normalising their length in relation to the total tooth size. On the reference frame, the stage of maturation reached is used to assign the value 1, and the other stages are calculated in relation to the tooth lengths. Two modelling methods were used: a linear model (LM) and a generalised additive model (GAM, Hastie & Tibshirani, 1986). Based on the observations of Comte Philibert Guéneau de Montbelliard, Comte Georges-Louis Leclerc Buffon noted in 1777 that growth and maturation processes are not linear. There are variations in the rhythms of growth and maturation due to hormonal, nutritional, environmental and metabolic factors (Falkner and Tanner, 1978). These age-dependent variations in rhythm and amplitude are reflected in tooth formation processes (Cameron, 1978; Buckberry, 2018). We therefore chose to model tooth maturation as a function of age by implementing a GAM (Wood, 2017) using the mgcv package (Wood, 2011). We also applied linear modelling as LMs are good descriptive tools for measuring the effect of most auxological parameters (Cheung, 2013, p. 73). As such, they provide a simple and robust means of proposing an age class based on tooth maturation (Hillson, 2005; Reid & Dean, 2006). They are suitable for working with small-amplitude age classes where the processes are linear (Buckberry, 2018, p. 64). They are therefore particularly useful for aligning sections made on teeth still forming, where the LM is sufficient and the data size makes it difficult to establish reliable GAMs. We created these models using the lm() function in the stats package (R core Team, 2024). The final step is to invert the model to predict ages according to maturation stages and, more specifically, to predict ages according to the sections of the tooth under study (Figure 2).

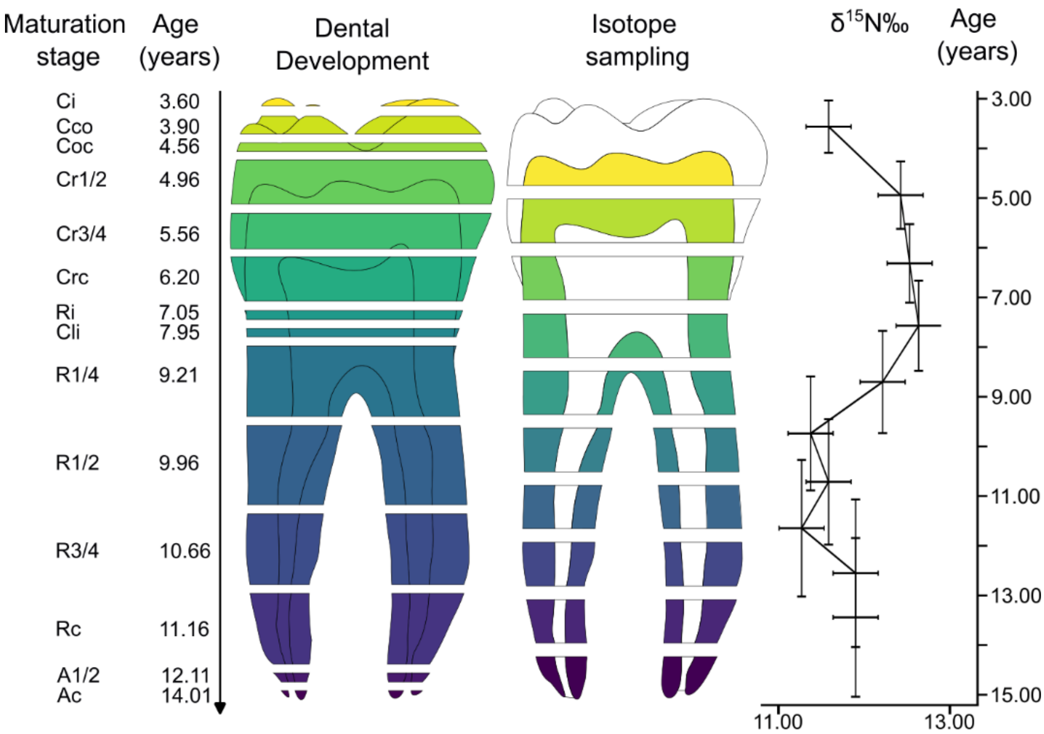

Figure 2 - Principle of the alignment of isotope sampling to the dental maturation referential in order to calculate the age at formation of each section and create the isobiography. The example uses the data obtained for the M2 of the individual 8, the Moorrees et al. referential and a GAM model.

Results

The raw data per tooth includes the following information: Section ID, anatomical region to which it belongs, its length, and $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values (Table 3). The protocol for estimating the formation age of dentine sections calculates minimum, mean and maximum ages per section. Estimates for individual 8 (C314 Sep 8) are shown in Figure 3. All results are presented in SI.

Discussion

Modelling dental development reliably

To compare LMs and GAMs, we modelled them for all data from both tooth development references and then calculated adjusted coefficients of determination (R^2adj), which measure the ratio of variance explained by the model to total variance (Dodge, 2007). Adjusted coefficients of determination are indicators of model quality and can have values between 0 and 1. If the values are close to 1, the variance explained is very close to the total variance and the model is considered satisfactory. We also compared the Akaike Information Criteria (AIC) of the LMs and GAMs to determine which model was best at describing the correlations. The AIC (Akaike, 1973) is a measure of the quality of a model by estimating the loss of information caused by its use. In our case, the model with the lowest AIC is considered to best describe the tooth mineralisation process.

The results for the Moorrees et al. referential are shown in Table 4 and those for the AlQahtani et al. referential are shown in Table 5.

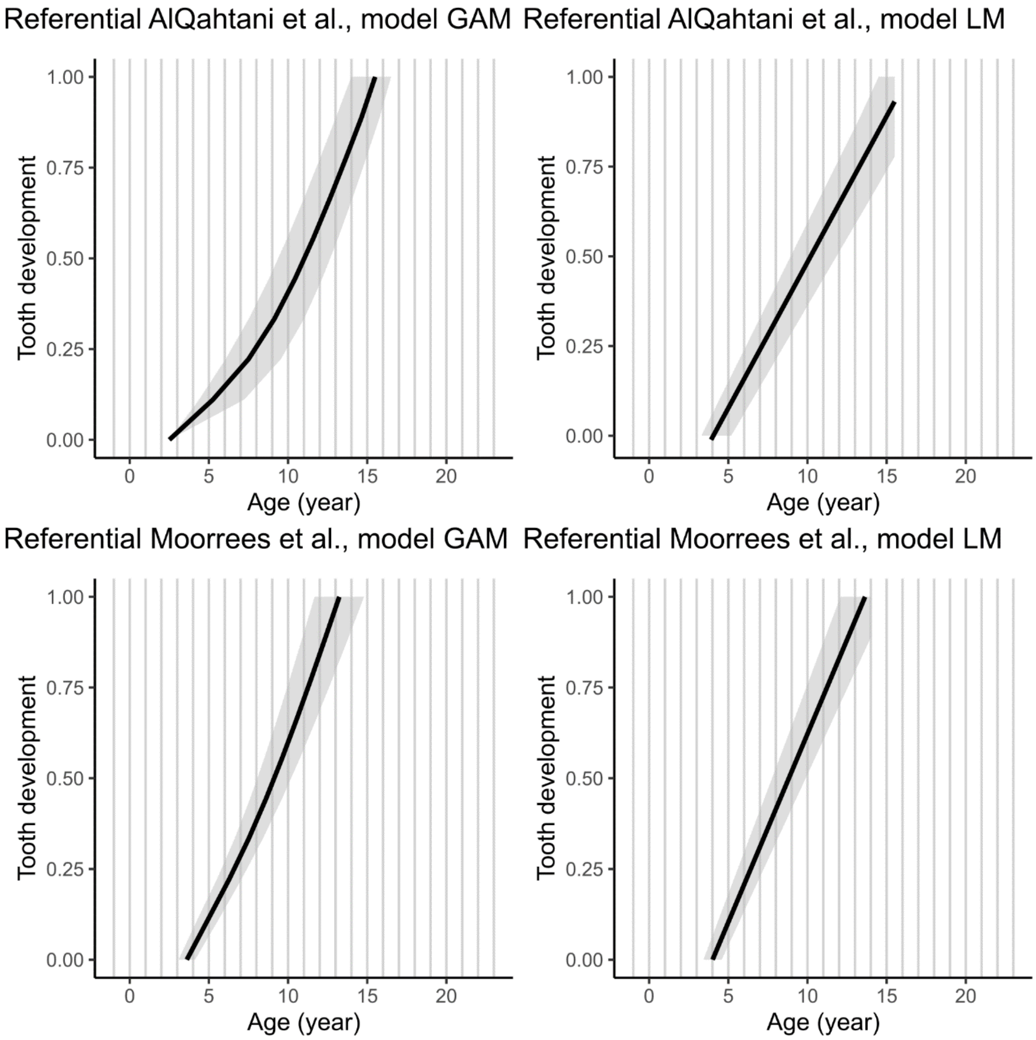

Figure 3 - Comparison of modelisations of age of mineralisation for the tooth M2 inferior of individual 8 using both references (Moorrees et al., 1963a; Moorrees et al., 1963b; AlQahtani et al., 2010) and both mathematical models (Linear Model and Generalised Additive Model). The black line represents the mean age and the grey areas the min and max ages.

Table 3 - Input and output data for the individual 8 using AlQahtani et al. and Moorrees et al. references and LM and GAM model. Input: Sections length and anatomical position (C = crown; RC = crown-root junction; R = root; A = apex) with elemental and stable isotope compositions of carbon, nitrogen and sulfur and elemental ratios. Output: minimal, mean and maximal age estimation for each section by refrerences and model. Low elemental compositions are not reported in the tables and isotopic composition of bad preserved sections are removed (= failed). Preservation criteria follows international recommendations (DeNiro, 1985; Ambrose & Norr, 1993; van Klinken, 1999; Nehlich, 2015)

Brézet C314 Sep 8	Section length (mm)	$\delta^{13}C$ (%)	$\delta^{15}N$ (%)	$\delta^{34}S$ (%)	%C	%N	%S	C:N Ratio	C:S Ratio	N:S Ratio	AlQahtani et al. GAM age min (years)	AlQahtani et al. GAM age med (years)	AlQahtani et al. GAM age max (years)	AlQahtani et al. LM age min (years)	AlQahtani et al. LM age med (years)	AlQahtani et al. LM age max (years)	Moorrees et al. GAM age min (years)	Moorrees et al. GAM age med (years)	Moorrees et al. GAM age max (years)	Moorrees et al. LM age min (years)	Moorrees et al. LM age med (years)	Moorrees et al. LM age max (years)
C10	2.65	-20.5	11.6	4.5	44.1	15.6	0.17	3.3	677	206	2.50	2.50	2.50	3.31	3.91	5.17	3.09	3.61	4.12	3.44	4.01	4.57
C9	1.65	-20.4	12.4	4.7	43.8	15.7	0.19	3.3	601	184	4.39	5.26	7.23	4.56	5.34	6.65	4.29	4.95	5.61	4.40	5.08	5.75
R8	1.65	-20.6	12.5	4.3	43.1	15.7	0.2	3.2	576	180	6.06	7.50	9.53	5.81	6.76	8.13	5.52	6.29	7.06	5.36	6.15	6.93
R7	1.65	-20.4	12.6	5.6	44	15.5	0.19	3.3	607	184	7.53	9.14	11.00	7.07	8.19	9.61	6.63	7.51	8.40	6.32	7.22	8.11
R6	1.65	-20.3	12.2	5.5	44.9	15.9	0.21	3.3	566	171	8.81	10.45	12.15	8.32	9.61	11.08	7.61	8.62	9.62	7.29	8.29	9.29
R5	1.65	-20	11.4	4.7	41.8	15.5	0.16	3.1	719	229	9.95	11.60	13.15	9.57	11.03	12.56	8.51	9.63	10.75	8.25	9.36	10.47
R4	1.65	-20.1	11.6	5.1	42.2	15.8	0.16	3.1	706	227	11.02	12.66	14.07	10.83	12.46	14.04	9.35	10.58	11.81	9.21	10.43	11.65
R3	1.65	-20.5	11.3	3.1	42.2	14.9	0.18	3.3	637	193	12.04	13.67	14.94	12.08	13.88	15.50	10.15	11.49	12.83	10.17	11.5	12.82
R2	1.65	-20.4	11.9	2.8	43.2	15.2	0.17	3.3	699	211	13.03	14.64	15.78	13.33	15.31	15.50	10.92	12.37	13.82	11.13	12.57	14.00
A1	1.65	-20.7	11.9	2.2	43.6	14.1	0.15	3.6	757	210	14.00	15.50	16.50	14.50	15.50	15.50	11.68	13.24	14.79	12.10	13.64	14.02

Table 4 - R^2 and AIC of different models using Moorrees et al. reference (Moorrees et al., 1963a; Moorrees et al., 1963b).

	Moorrees et al. NA					Moorrees et al. F					Moorrees et al. M				
	GAM		LM		GAM VS LM	GAM		LM		GAM VS LM	GAM		LM		GAM VS LM
Tooth	AIC	R^2adj	AIC	R^2adj	Lowest AIC	AIC	R^2adj	AIC	R^2adj	Lowest AIC	AIC	R^2adj	AIC	R^2adj	Lowest AIC
cinfmin	11.412	0.995	39.909	0.936	GAM	18.461	0.991	38.142	0.945	GAM	63.078	0.473	63.078	0.473	Equivalent
cinfmed	9.178	0.996	39.895	0.936	GAM	16.879	0.993	38.195	0.945	GAM	61.456	0.546	61.456	0.546	Equivalent
cinfmax	13.786	0.994	40.095	0.935	GAM	15.526	0.993	38.253	0.945	GAM	59.126	0.645	59.914	0.605	GAM
m1infmin	26.616	0.974	30.999	0.957	GAM	27.370	0.972	31.147	0.956	GAM	20.475	0.986	35.855	0.930	GAM
m1infmed	20.617	0.986	32.541	0.950	GAM	25.857	0.976	30.964	0.957	GAM	21.454	0.985	35.591	0.932	GAM
m1infmax	22.249	0.983	35.383	0.933	GAM	24.675	0.979	30.868	0.958	GAM	22.249	0.983	35.383	0.933	GAM
m2infmin	18.292	0.989	22.447	0.982	GAM	18.650	0.988	22.530	0.982	GAM	29.044	0.967	32.751	0.949	GAM
m2infmed	23.641	0.981	28.435	0.967	GAM	18.390	0.989	22.733	0.981	GAM	28.346	0.969	32.645	0.949	GAM

m2infmax	27.923	0.970	32.735	0.949	GAM	18.211	0.989	22.929	0.981	GAM	27.923	0.970	32.735	0.949	GAM
I1supmin	-0.876	0.998	13.176	0.975	GAM	-0.876	0.998	13.176	0.975	GAM	3.120	0.995	11.527	0.971	GAM
I1supmed	1.707	0.996	11.278	0.982	GAM	0.120	0.997	13.031	0.975	GAM	2.847	0.995	11.541	0.971	GAM
I1supmax	7.118	0.991	11.572	0.981	GAM	0.885	0.997	12.916	0.976	GAM	2.616	0.995	11.553	0.971	GAM
I2supmin	3.473	0.995	16.123	0.959	GAM	3.215	0.995	16.249	0.958	GAM	-8.300	0.999	13.757	0.955	GAM
I2supmed	7.060	0.991	14.772	0.967	GAM	3.569	0.995	16.277	0.958	GAM	-5.103	0.999	13.890	0.954	GAM
I2supmax	10.785	0.984	14.919	0.966	GAM	3.863	0.995	16.301	0.957	GAM	-3.052	0.998	14.004	0.953	GAM
I1infmin	1.454	0.993	9.586	0.966	GAM	1.454	0.993	9.586	0.966	GAM	-184.236	1.000	-205.044	1.000	Equivalent
I1infmed	1.051	0.994	9.536	0.966	GAM	1.051	0.994	9.536	0.966	GAM	-184.236	1.000	-205.044	1.000	Equivalent
I1infmax	0.722	0.994	9.499	0.966	GAM	0.722	0.994	9.499	0.966	GAM	-184.236	1.000	-205.044	1.000	Equivalent
I2infmin	4.940	0.986	4.940	0.986	Equivalent	4.940	0.986	4.940	0.986	Equivalent	-16.995	1.000	-16.553	1.000	GAM
I2infmed	-2.647	0.997	-1.007	0.996	GAM	4.966	0.986	4.966	0.986	Equivalent	-184.236	1.000	-205.044	1.000	Equivalent
I2infmax	-1.806	0.997	-0.970	0.996	GAM	4.999	0.986	4.999	0.986	Equivalent	-31.899	1.000	-17.613	1.000	GAM
Cinfmin	5.824	0.984	5.824	0.984	Equivalent	5.824	0.984	5.824	0.984	Equivalent	-14.779	1.000	-4.888	0.998	GAM
Cinfmed	5.661	0.984	5.661	0.984	Equivalent	5.614	0.984	5.614	0.984	Equivalent	-19.248	1.000	-4.802	0.998	GAM
Cinfmax	5.606	0.984	5.606	0.984	Equivalent	5.443	0.985	5.443	0.985	Equivalent	-7.032	0.999	-4.731	0.998	GAM
Pm1infmin	11.324	0.951	11.324	0.951	GAM	11.324	0.951	11.324	0.951	GAM	-55.625	1.000	3.428	0.968	GAM
Pm1infmed	10.783	0.956	10.783	0.956	GAM	10.783	0.956	10.783	0.956	GAM	-68.196	1.000	3.116	0.971	GAM
Pm1infmax	10.335	0.960	10.335	0.960	GAM	10.335	0.960	10.335	0.960	GAM	1.116	0.982	2.847	0.974	GAM
P2infmin	1.480	0.993	9.816	0.964	GAM	1.480	0.993	9.816	0.964	GAM	-18.006	1.000	-17.372	1.000	GAM
Pm2infmed	2.221	0.992	6.173	0.983	GAM	1.294	0.993	9.505	0.966	GAM	-173.113	1.000	-194.294	1.000	Equivalent
P2infmax	2.012	0.993	2.607	0.991	GAM	1.138	0.994	9.244	0.968	GAM	-18.887	1.000	-18.626	1.000	GAM
M1infmin	8.577	0.972	15.461	0.888	GAM	2.616	0.991	12.083	0.943	GAM	-67.273	1.000	8.339	0.836	GAM
M1infmed	3.717	0.989	17.027	0.847	GAM	3.350	0.990	12.553	0.938	GAM	4.487	0.932	7.962	0.855	GAM
M1infmax	-2.554	0.997	18.052	0.813	GAM	3.945	0.989	12.932	0.933	GAM	6.325	0.904	7.632	0.870	GAM
M2infmin	-0.285	0.995	12.857	0.934	GAM	-0.285	0.995	12.857	0.934	GAM	0.566	0.985	2.294	0.978	GAM
M2infmed	1.008	0.994	11.796	0.946	GAM	-1.841	0.996	12.937	0.933	GAM	-4.529	0.995	1.656	0.982	GAM
M2infmax	1.795	0.993	10.826	0.956	GAM	-3.275	0.997	13.008	0.932	GAM	1.031	0.986	1.079	0.985	GAM
M3infmin	-0.020	0.995	16.338	0.867	GAM	6.764	0.981	12.321	0.940	GAM	-14.106	1.000	-13.994	1.000	GAM
M3infmed	0.666	0.994	14.270	0.912	GAM	7.196	0.979	12.490	0.938	GAM	-192.547	1.000	-190.135	1.000	GAM
M3infmax	7.556	0.977	12.635	0.937	GAM	7.556	0.977	12.635	0.937	GAM	-77.896	1.000	-15.285	1.000	GAM

Table 5 - R^2 and AIC of differents models using AlQahtani et al. reference (AlQahtani et al., 2010).

	AlQahtani et al.				
	GAM		LM		GAM VS LM
Tooth	AIC	R²adj	AIC	R²adj	Lowest AIC
i1supmin	53.242	0.920	62.019	0.834	GAM
i1supmed	40.072	0.971	56.752	0.889	GAM
i1supmax	47.710	0.946	48.218	0.943	GAM
i2supmin	48.976	0.942	57.826	0.880	GAM
i2supmed	42.662	0.964	49.233	0.938	GAM
i2supmax	53.116	0.916	53.116	0.916	Equivalent
csupmin	34.275	0.981	45.994	0.952	GAM
csupmed	39.515	0.972	41.969	0.964	GAM
csupmax	44.124	0.958	44.156	0.958	GAM
m1supmin	34.539	0.981	58.197	0.876	GAM
m1supmed	39.681	0.971	40.768	0.968	GAM
m1supmax	39.726	0.971	41.435	0.966	GAM
m2supmin	40.253	0.970	44.067	0.958	GAM
m2supmed	43.464	0.960	43.464	0.960	Equivalent
m2supmax	40.379	0.962	40.379	0.962	Equivalent
i1infmin	49.115	0.927	59.628	0.813	GAM
i1infmed	41.913	0.960	57.386	0.845	GAM
i1infmax	37.742	0.972	47.133	0.934	GAM
i2infmin	50.853	0.915	55.995	0.862	GAM
i2infmed	42.050	0.959	51.620	0.904	GAM
i2infmax	38.584	0.969	47.158	0.934	GAM
cinfmin	42.795	0.954	42.795	0.954	Equivalent
cinfmed	34.146	0.979	37.924	0.969	GAM
cinfmax	43.530	0.951	43.530	0.951	Equivalent
m1infmin	41.307	0.960	41.684	0.958	GAM
m1infmed	37.500	0.970	37.503	0.970	GAM
m1infmax	43.481	0.953	44.817	0.946	GAM
m2infmin	35.314	0.977	43.241	0.952	GAM
m2infmed	42.051	0.957	42.051	0.957	Equivalent
m2infmax	41.445	0.959	41.445	0.959	Equivalent
I1supmin	39.338	0.967	40.223	0.963	GAM
I1supmed	38.834	0.967	38.834	0.967	Equivalent
I1supmax	35.389	0.975	35.389	0.975	Equivalent
I2supmin	46.048	0.942	47.221	0.934	GAM
I2supmed	37.977	0.969	37.977	0.969	Equivalent
I2supmax	35.083	0.976	35.083	0.976	Equivalent
Csupmin	27.176	0.988	42.298	0.956	GAM
Csupmed	28.125	0.987	29.867	0.984	GAM
Csupmax	24.341	0.990	24.341	0.990	Equivalent
Pm1supmin	26.212	0.988	26.212	0.988	Equivalent
Pm1supmed	18.568	0.994	18.568	0.994	Equivalent
Pm1supmax	35.913	0.974	35.913	0.974	GAM
Pm2supmin	36.748	0.972	36.748	0.972	GAM

Pm2supmed	19.451	0.993	19.451	0.993	Equivalent
Pm2supmax	33.213	0.979	33.213	0.979	Equivalent
M1supmin	32.048	0.982	32.598	0.980	GAM
M1supmed	25.084	0.989	25.084	0.989	Equivalent
M1supmax	39.515	0.965	39.515	0.965	Equivalent
M2supmin	30.392	0.985	40.179	0.963	GAM
M2supmed	15.542	0.995	15.542	0.995	Equivalent
M2supmax	38.999	0.967	38.999	0.967	Equivalent
M3supmin	31.033	0.984	42.483	0.955	GAM
M3supmed	21.497	0.992	21.497	0.992	Equivalent
M3supmax	43.366	0.954	45.064	0.944	GAM
I1infmin	42.355	0.957	43.684	0.951	GAM
I1infmed	30.467	0.984	32.025	0.981	GAM
I1infmax	33.543	0.979	33.543	0.979	Equivalent
I2infmin	41.603	0.958	41.603	0.958	Equivalent
I2infmed	28.630	0.986	29.377	0.985	GAM
I2infmax	36.404	0.973	36.404	0.973	Equivalent
Cinfmin	38.735	0.969	40.098	0.963	GAM
Cinfmed	23.579	0.991	27.186	0.987	GAM
Cinfmax	20.341	0.993	23.109	0.991	GAM
Pm1infmin	32.267	0.982	33.866	0.978	GAM
Pm1infmed	15.060	0.995	15.060	0.995	Equivalent
Pm1infmax	34.868	0.976	34.868	0.976	Equivalent
Pm2infmin	33.180	0.980	34.562	0.977	GAM
Pm2infmed	29.324	0.986	31.563	0.982	GAM
Pm2infmax	33.504	0.979	33.504	0.979	Equivalent
M1infmin	24.514	0.991	31.658	0.982	GAM
M1infmed	28.385	0.987	29.960	0.984	GAM
M1infmax	41.856	0.959	43.333	0.952	GAM
M2infmin	24.511	0.991	29.798	0.984	GAM
M2infmed	15.542	0.995	15.542	0.995	Equivalent
M2infmax	29.205	0.986	37.364	0.971	GAM
M3infmin	45.423	0.946	50.611	0.912	GAM
M3infmed	34.298	0.977	34.298	0.977	Equivalent
M3infmax	38.353	0.968	38.353	0.968	Equivalent

The results show that the various models are satisfactory, with the exception of those for lower deciduous canines on the Moorrees et al. male reference frame, for which the adjusted R^2s of LM and GAM do not exceed 0.65. Our analysis protocol is therefore unsuitable for working on decidual canines using the Moorrees et al. reference for boys. For all teeth, the GAMs have lower or equal AICs than the LMs. GAMs are therefore best suited to describe tooth mineralisation processes. However, when tooth maturation is incomplete, GAMs have fewer reference points, which reduces their reliability. If only the crown or root is being studied, an LM is preferable.

Impact of accounting standards chosen on interpretations

Substantial differences in age estimates are found depending on the choice of statistical model and frame of reference. For the same frame of reference, a difference in model can lead to a difference of 2.67 years, and for the same model, a difference in frame of reference can lead to a difference of 3.39 years. The choice of reference frame can introduce a bias in the interpretation of the results obtained. Over- or underestimation of age can further complicate data analysis. Social changes are often, although not systematically, inferred from biological transformations such as puberty and/or growth, which allow individuals to access new functions due to their physical or biological development (Bocquentin, 2003; Barbot & Hunter, 2012). Thus, an error in age estimation may hinder the identification of the initial cause of the observed change and, consequently, the interpretation of the results. AlQahtani et al. is based on the observation of the presence of maturation stages for a given age in a set of individuals, whereas Moorrees et al. notes the age of appearance of the stages in longitudinal data and distinguishes between the sexes. In this way, Moorrees et al. standards records variations in the rate of mineralisation as a function of age, a phenomenon that is less apparent in AlQahtani et al. data. This essential point makes the Moorrees et al. reference the preferred choice where applicable, as it is closer to the physiological reality of the dental mineralisation process. Secular variations in pubertal age (Parent et al., 2003) appear to be due to a combination of socio-economic factors (Huen et al., 1997; Krstevska-Konstantinova et al., 2001; Teilmann et al., 2006), nutritional factors (Stark et al., 1989; Wang, 2002; Sloboda et al., 2007; Lee et al., 2007), genetic factors (Guo et al., 2006; Rothenbuhler et al., 2006; Zhou et al., 2007) and stresses experienced during growth and development (Theintz et al., 1989; Georgopoulos et al., 1999). In addition, the social responses associated with biological changes are fundamental to understanding the populations studied. For example, the accuracy of age estimation in relation to sex is crucial in studies of gender and differences between boys and girls. These elements can inform us about the social organisation of societies (patrilocality vs. matrilocality, inequality vs. cooperation between the sexes, intersectionality in the definition of gender), where differences may emerge as early as childhood. For this reason, the use of the Moorrees et al. reference, which differentiates dental development according to sex, is preferable. Furthermore, the age of weaning in Palaeolithic hunter-gatherer societies, for example, is an essential element in understanding these populations (Ellison, 1995). In a nomadic society, the dependence of the young child on the group, and in particular on the nursing mother (who may be a woman other than the biological mother), affects the whole community. Travelling, migration and group size are partly determined by this practice (Waters-Rist, 2019). Overestimating or underestimating the age of weaning can therefore distort our interpretations in an archaeological context. Finally, with regard to the social age classes that we seek to identify using this method, any error in age estimation can also affect the definition of age pivots, thus distorting the intervals that mark social transitions and, consequently, our understanding of group functioning.

On the basis of the figures proposed in SI, we discuss below the comparison of the two frames of reference (Figure 4) in the context of a bioanthropological and archaeological interpretation. Individual 8 (C314 Sep 8) with the GAM model is chosen as the first example. Firstly, we can see that changes in the isotopic profiles for each of the elements are recorded at different ages depending on the reference frame. In the case of carbon, the variation in isotopic composition throughout childhood is limited to between -20.5 and -20.0‰, which is consistent with the local environment and the isotopic values recorded on bone collagen (cf. SI). Here, the time lag of about 2 years observed between the two reference frames (cf. vertical lines) is not controversial, as an environmental change is not clearly supported by the $\delta^{13}C$ value. On the other hand, for the $\delta^{15}N$ value, we observe a decrease of 1.3‰, which is observed at approx. 9.5 years using AlQhatani et al. and at ca. 7.5 years according to Moorrees et al., which is accompanied by a decrease in $\delta^{34}S$ value of 3.4‰ at ca. 10 years (AlQhatani et al) or ca. 8 years (Moorrees et al.). These roughly related changes for these two isotopic compositions show a move away for S and a move closer for N compared to the values recorded on bone. These changes could indicate a change in dietary protein sources and/or mobility in an environment with little variation in $\delta^{13}C$ for about two years. At 11.5 years according to AlQhatani et al. and ca. 9.5 years using Moorrees et al., the $\delta^{15}N$ value of the dentine increases slightly, but for sulfur the $\delta^{34}S$ recorded value continues to decrease and deviate from the variability recorded on the adult bones of Le Brézet and other Neolithic individuals from the area. If we rely primarily on $\delta^{34}S$ value to discuss a change during the life of the individual (in this case, mobility), we find that the two pivotal ages according to the chosen frame of reference are close to what has been observed in other Neolithic groups, notably at Gurgy (Yonne, France) (first proposed changes around age 8 using AlQahtani et al. frame of reference, Rey et al. 2021). Consequently, if we wish to establish a precise age for large-scale statistical comparisons, the difference of two years between the two models is unacceptable. However, in the case of a broader age estimate (e.g. infancy, childhood, pre-adolescence, adolescence), which would only allow us to identify a moment in life or a moment of "maturity", the observed age gap allows for empirical reflection, which must then be confronted on a case-by-case basis with other archaeological (e.g. grave goods, body position, cf. Le Roy 2015) and biological data. In the case of Le Brézet, the hypothesis of an environmental or dietary change around the age of 8 is not observed for other M2s (cf. SI), for which other isotopic variations occur well before this age range, for example for individual 4.

As the intra-individual comparative approach shows, the choice of reference frame for dental maturation can strongly modify the interpretation of the data. These results reflect two findings already observed in studies of the reliability of such reference frames: AlQahtani et al. tends to overestimate age in many populations (Sousa et al., 2020; Alkandiri et al., 2021; Vila-Blanco et al., 2023), while Moorrees et al. tends to underestimate age (Liversidge et al., 2010; Tony L. et al., 2016; Alkandiri et al., 2021; AlOtaibi & AlQahtani, 2023; Vila-Blanco et al., 2023). These phenomena, which are difficult to quantify in prehistoric populations, must be considered when interpreting results, especially when inferences of social age based on dental age are proposed (Rey et al., 2021).

Impact of choice of statistical model on interpretations

In the second example chosen, Individual 2 (Sep 2) presents only isotopic profiles of M1 dentine from the AlQhatani et al. reference data (GAM and LM shown in Figure 5). Based on bone maturation, the child's age at death is estimated to be between 5.5 and 10 years. The tooth examined was not complete at the time of death, so the last section of dentine recorded the very last moments of life. The isotopic profiles of the dentine are consistent for carbon and nitrogen, whatever the model for this Individual. A first 'break' can be seen at around 3 years of age, which may mark the complete end of the child's weaning period. For these two elements, a second "break" can be suggested at around 7.5 to 8 years of age. In contrast to Brézet's other individual, who died later in adulthood, Individual 2 may have been exposed to unfavourable physiological and sanitation conditions, which may have led to an early death. The very last section of dentine shows a decrease in $\delta^{13}C$ value and an increase in $\delta^{15}N$ value. This type of pattern is regularly observed in archaeology for the dentine of immatures (e.g. tuberculosis cases, Goude et al., 2020a) and may be related to metabolic disturbances, including remobilisation of body proteins and lipid reserves in cases of malnutrition, as shown by several studies in medical settings (Mekota et al., 2006; Neuberger et al., 2013) and during starvation episodes (Beaumont & Montgomery, 2016). In contrast to the example described above, here the estimation of age at death may have a greater impact on archaeological interpretations. The end of lactation and weaning are crucial moments in an individual's life, and accurately estimating this transition to solid food incorporates the many discourses in the literature about female fertility and childcare, indicators of population survival. On a growing tooth, the estimation of the age at death, especially for an individual marked by a possible indicator of poor nutritional status, allows the refinement of an age that is sometimes too broad, based on bone measurements. Estimates of the age of formation of dentine sections are subject to a variable margin of uncertainty, depending on the model used. A discrepancy of 1, 2 or even more years is therefore unacceptable for these scientific purposes.

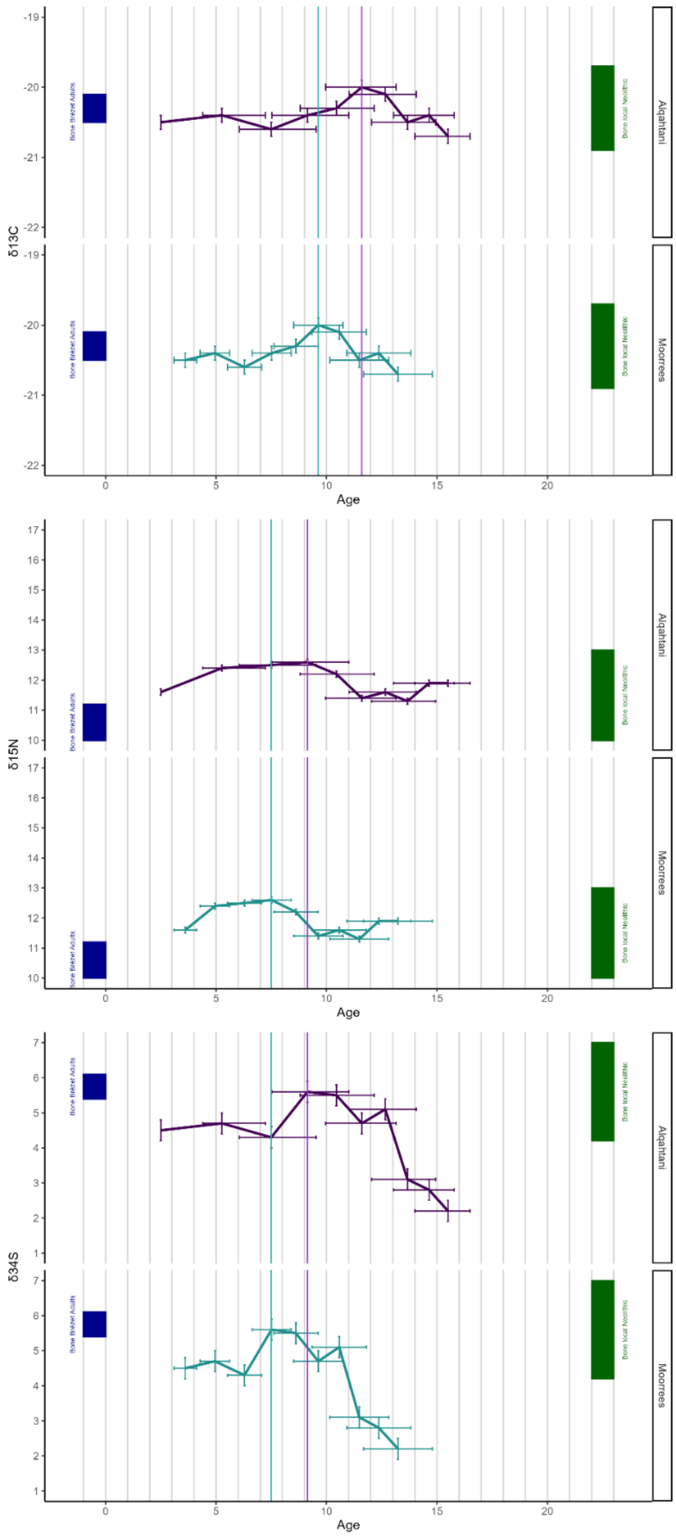

Figure 4 - Isotopic compositions of dentine sections from Individual Brézet 8 (M2, female) as a function of an age estimate based on the GAM model and according to the reference (AlQahtani et al., 2010) (purple) and (Moorrees et al., 1963a; Moorrees et al., 1963b) (green). Variations in bone isotope compositions recorded for Brézet (blue, this study, N = 3) and for another Neolithic series from Clermont Ferrand (Goude et al., 2013, 2025, N Carbon and Nitrogen = 38, N Sulfur = 37) are reported. The standard deviation on the isotopic measurement is reported for each element (between ± 0.25‰ and ±0.14‰). Coloured vertical lines indicate a discussed breakpoint for each curve.

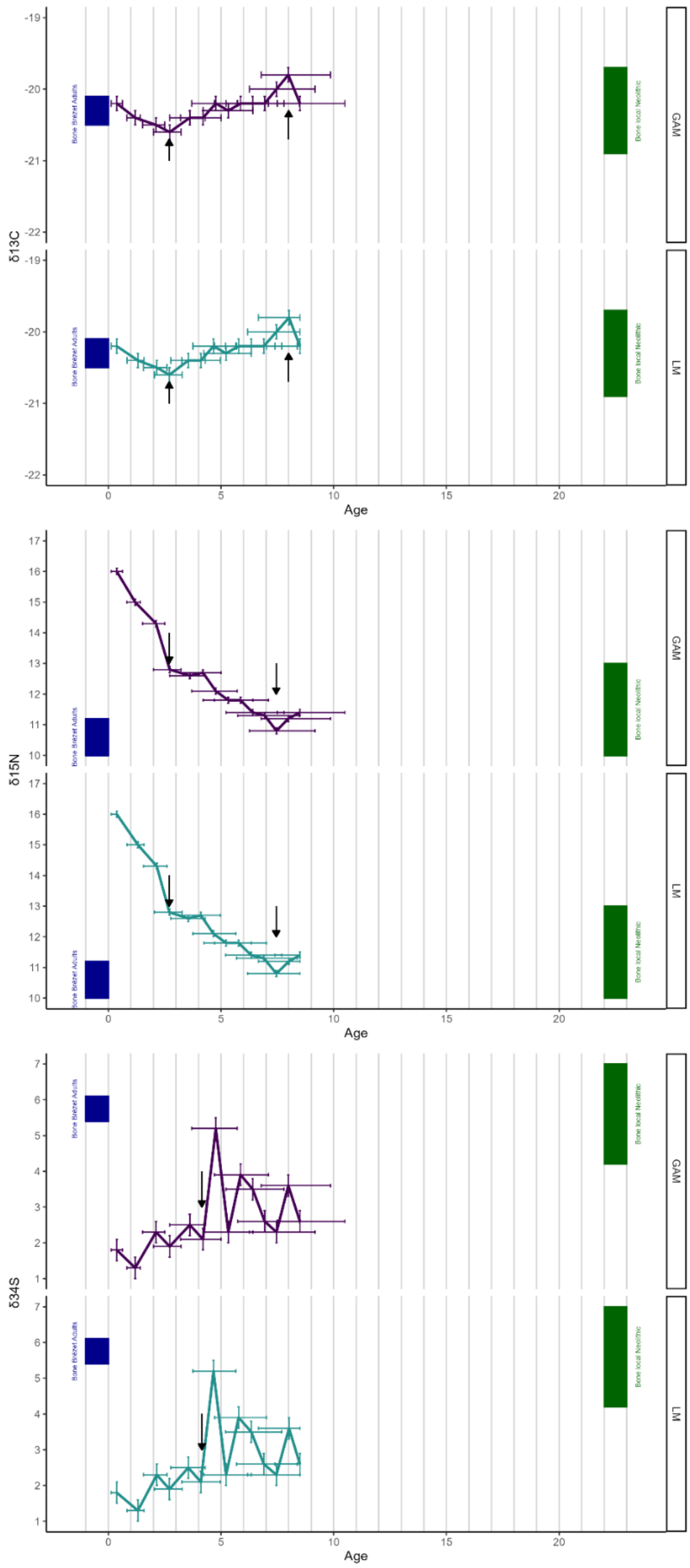

Figure 5 - Isotopic compositions of dentine sections from Individual Brézet 2 (M1) as a function of an age estimate based on the GAM and LM models and according to the AlQhatani et al. reference. Variations in bone isotopic compositions recorded for Brézet (blue, this study, N = 3) and for another Neolithic series from Clermont Ferrand (Goude et al., 2013, 2025, N Carbon and Nitrogen = 38, N Sulfur = 37) are reported. The standard deviation on the isotopic measurement is reported for each element (between ± 0.25‰ and ±0.14‰). Arrows indicate a discussed breakpoint for each curve.

Conclusion

The life histories of ancient populations and the possibilities of longitudinal analysis are topics that are increasingly being incorporated into archaeological studies, encouraging new ways of thinking about the mutability of people's statuses over the course of their lives. This approach allows us to move away from fixed, 'binary' interpretations and to shed new light on intra- and inter-, individual- and population-level variability. When applied to the Neolithic, the concept of 'social ages', which combines archaeological and biological data, changes our understanding of population dynamics. These 'social ages' can be partially identified by isobiography, making it an increasingly popular approach to the study of ancient populations. However, the interest of this method is accompanied by limitations related, on the one hand, to the biology of growth and, on the other, to the application of current references to past populations. In this context, the ANR WomenSOFar project, which aims to understand the variability of social status between men and women over the course of their lives, has studied the isobiography of several Neolithic individuals in France and the Mediterranean. Among these individuals, those from the site of Le Brézet provide the first keys to understanding a chronocultural context that is already well documented from both archaeological and anthropological points of view: the French Middle Neolithic (4500-3500 BCE).

In order to study the variations in $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ isotopic values along dental sections, we propose a statistical analysis protocol to estimate the formation age of the different sections according to the choices specific to each researcher. We used the two dental maturation reference frames most widely used in the international biological anthropology community (Moorrees et al., 1963a; Moorrees et al., 1963b; AlQahtani et al., 2010) and tested two types of modelling: linear models (LM) and generalised additive models (GAM). Our results show that GAMs are best suited to describe the non-linear process of tooth mineralisation. However, LMs remain reliable and adequate, particularly when it comes to studying teeth in the process of formation or resorption. The data provided by the Moorrees et al. studies are preferable for modelling because (1) they are longitudinal, (2) mineralisation rates can be differentiated by sex, and (3) the measurements correspond to numerical ages rather than age classes. However, AlQahtani et al. covers the entire deciduous and permanent dentition, whereas Moorrees et al. is based on the observation of three deciduous teeth (lower c, m1 and m2) and ten permanent teeth (maxillary I and all mandibular teeth). The choice of teeth therefore determines the frame of reference to be used. Both reference frames are also subject to age overestimation and underestimation biases, the effects of which on prehistoric populations are poorly understood.

Although exploratory, this work demonstrates that an isobiographical study based on dentinal sections must first take into account the preservation and availability of dental material. This inventory defines the potential for analysis and interpretation and can be used as a decision-making tool to optimise data collection in relation to the invasive impact on the sample. We therefore recommend anticipating and projecting the type of data expected, as well as considering potential and already identified interpretative biases, before requests to collect archaeological material are proposed and/or granted. If a single individual is being studied, we recommend that all models be run, and the different results taken into account when making inferences about biological age. If a series is being studied or several individuals are being compared, it is preferable to use a single model and a single frame of reference to make the data comparable, while recognising the inherent limitations of mathematical models and frames of reference.

Formatted versions of the referentials and an annotated version of the R script are provided in SI. The script is optimised for formatted data in the same way as the input data in Table 3.

Acknowledgements

The authors thank the SRA Auvergne Rhône Alpes for the sampling authorisation, Muriel Gandelin and Christelle Gaudelet from INRAP and Patrice Courtaud (PACEA) for the management of the collection. We would also like to thank Anaïs Baima-Rughet (Aix-Marseille University) for technical assistance during her master's thesis and Guy André (UMR 7269 LAMPEA) for his help with tooth cutting.

Preprint version 2 of this article has been peer-reviewed and recommended by Peer Community In Archaeology (https://doi.org/10.24072/pci.archaeo.100609; Leggett, 2025).

Fundings

This work was funded by the French National Research Agency (ANR WomenSOFar 21-CE03-0008) https://womensofar.hypotheses.org/.

Conflict of interest disclosure

The authors declare that they have no known competing financial interests or personal relationships that could potentially influence the work reported in this paper. Gwenaëlle Goude is recommender for the PCI Archaeology.

Data, script, code and supplementary Information availability

All supplementary informations are available at https://doi.org/10.5281/zenodo.15124498 (Bédécarrats et al., 2025).

References

Akaike H (1973) Information theory and an extension of the maximum likelihood principle. *2nd Int. Symp. Information Theory, Akademia Kiado, Budapest, 1973*.

Alkandiri F, Karimi A, Draft D, Lucas VS, Roberts G (2021) Dental Age Estimation: A comparison of three methods of estimating dental age in a population of Kuwaiti children and adolescents. *Forensic Science International: Reports*, **3**, 100214. https://doi.org/10.1016/j.fsir.2021.100214

AlOtaibi NN, AlQahtani SJ (2023) Performance of different dental age estimation methods on Saudi children. *The Journal of Forensic Odonto-stomatology*, **41**, 27–46.

AlQahtani SJ, Hector MP, Liversidge HM (2010) Brief communication: The London atlas of human tooth development and eruption. *American Journal of Physical Anthropology*, **142**, 481–490. https://doi.org/10.1002/ajpa.21258

Ambrose SH, Norr L (1993) Experimental Evidence for the Relationship of the Carbon Isotope Ratios of Whole Diet and Dietary Protein to Those of Bone Collagen and Carbonate. In: *Prehistoric Human Bone: Archaeology at the Molecular Level* (eds Lambert JB, Grupe G), pp. 1–37. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-02894-0_1

Anderson DL, Thompson GW, Popovich F (1976) Age of attainment of mineralization stages of the permanent dentition. *Journal of Forensic Sciences*, **21**, 191–200. https://doi.org/10.1520/jfs10353j

Arumugam DrV, Doggalli DrN (2020) Different Dental Aging Charts or Atlas Methods Used for Age Estimation–A Review. *Asian Journal of Basic Science & Research*, **02**, 64–74. https://doi.org/10.38177/AJBSR.2020.2306

Banerjee P, Mukherjee S (1967) Eruption of deciduous teeth among Bengalee children. *American Journal of Physical Anthropology*, **26**, 357–358. https://doi.org/10.1002/ajpa.1330260311

Barbot B, Hunter SR (2012) Developmental Changes in Adolescence and Risks for Delinquency. In: *Handbook of Juvenile Forensic Psychology and Psychiatry* (ed Grigorenko EL), pp. 11–34. Springer US, Boston, MA. https://doi.org/10.1007/978-1-4614-0905-2_2

Beaumont J, Atkins E-C, Buckberry J, Haydock H, Horne P, Howcroft R, Mackenzie K, Montgomery J (2018) Comparing apples and oranges: Why infant bone collagen may not reflect dietary intake in the same way as dentine collagen. *American Journal of Physical Anthropology*, **167**, 524–540. https://doi.org/10.1002/ajpa.23682

Beaumont J, Gledhill A, Lee-Thorp J, Montgomery J (2013) Childhood Diet: A Closer Examination of the Evidence from Dental Tissues Using Stable Isotope Analysis of Incremental Human Dentine*. *Archaeometry*, **55**, 277–295. https://doi.org/10.1111/j.1475-4754.2012.00682.x

Beaumont J, Montgomery J (2015) Oral histories: a simple method of assigning chronological age to isotopic values from human dentine collagen. *Annals of Human Biology*, **42**, 407–414. https://doi.org/10.3109/03014460.2015.1045027

Beaumont J, Montgomery J (2016) The Great Irish Famine: Identifying Starvation in the Tissues of Victims Using Stable Isotope Analysis of Bone and Incremental Dentine Collagen. *PLOS ONE*, **11**, e0160065. https://doi.org/10.1371/journal.pone.0160065

Bédécarrats S, Le Roy M, Sayle KL, Frédérique B, Couvrat M, Gleize Y, Leduc G, Rottier S, Goude G (2025) Supplementary Informations to Isobiography of the first farmers: effects of age-estimating referential and statistical models on reconstructing infant life, Bédécarrats et al. https://doi.org/10.5281/ZENODO.16363080

Bernardini S, Zeppilli C, Micarelli I, Goude G, Sayle KL, Manzi G, Tafuri MA (2023) Multi-isotope analysis of primary and secondary dentin as a mean to broaden intra-life dietary reconstruction. A case from Longobard Italy. *International Journal of Osteoarchaeology*, **33**, 355–360. https://doi.org/10.1002/oa.3200

Birkner R (1980) *L'image radiologique typique de squelette: aspect normal et variantes chez l'adulte et l'enfant; pour médecins, étudiants et manipulateurs*. Maloine.

Blaizot F (2005) Etude de l'occupation funéraire du Brézet. In: *Le Brézet rue Georges Besse, Clermont-Ferrand, Puy-de-Dôme, Rapport de fouille archéologique* (ed Vernet G), pp. 21–69. Inrap, Service régional de l'Archéologie Auvergne.

Blaizot F, Vernet G (2004) La tombe en fosse campaniforme sur le site Le Brézet, à Clermont-Ferrand (Puy-de-Dôme, France). In: *Graves and Funerary Rituals during the Late Neolithic and the Early Bronze Age in Europe (2700-2000 BC), Prooceedings of the International Conference held at the Cantonal Archaeological Museum, Sion (Switzerland) October 4th-7th 2001* BAR International Series. (eds Besse M, Desideri J), pp. 41–47. Archaeopress, Oxford (GB).

Bocquentin F (2003) Pratiques funéraires, paramètres biologiques et identités culturelles au Natoufien : une analyse archéo-anthropologique. These de doctorat Thesis. Université Bordeaux 1.

Brooks S, Suchey JM (1990) Skeletal age determination based on the os pubis: A comparison of the Acsádi-Nemeskéri and Suchey-Brooks methods. *Human Evolution*, **5**, 227–238. https://doi.org/10.1007/BF02437238

Brůžek J (1991) Fiabilité des procédés de détermination du sexe à partir de l'os coxal: implications à l'étude du dimorphisme sexuel de l'homme fossile. Thèse de doctorat Thesis. Muséum national d'histoire naturelle, Paris, France.

Brůžek J (1996) Interprétation biologique de séries archéologiques: impact d'une diagnose sexuelle erronée à partir de la simulation dans un échantillon de sexe connu. *L'identité des populations archéologiques*, **16**, 415–425.

Buckberry J (2018) Techniques for identifying the age and sex of children at death. In: *The Oxford Handbook of the Archaeology of Childhood* Oxford Handbooks. (eds Crawford SEE, Hadley DM, Shepherd G), pp. 55–70. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199670697.013.3

Cameron N (1978) The Methods of Auxological Anthropometry. In: *Human Growth: 2 Postnatal Growth* (eds Falkner F, Tanner JM), pp. 35–90. Springer US, Boston, MA. https://doi.org/10.1007/978-1-4684-2622-9_3

Carr LM (1962) Eruption ages of permanent teeth. *Australian Dental Journal*, **7**, 367–373. https://doi.org/10.1111/j.1834-7819.1962.tb04884.x

Cheung YB (2013) *Statistical Analysis of Human Growth and Development*. Chapman and Hall/CRC, New York. https://doi.org/10.1201/b15979

Christensen GJ, Kraus BS (1965) Initial Calcification of the Human Permanent First Molar. *Journal of Dental Research*, **44**, 1338–1342. https://doi.org/10.1177/00220345650440063701

Clements EMB, Davies-Thomas E, Pickett KG (1953) Time of eruption of permanent teeth in British children in 1947-8. *British medical journal*, **1**, 1421. https://doi.org/10.1136/bmj.1.4825.1421

Cocozza C, Fernandes R (2021) Amalthea: A Database of Isotopic Measurements on Archaeological and Forensic Tooth Dentine Increments. *Journal of Open Archaeology Data*, **9**. https://doi.org/10.5334/joad.75

Cohen JT (1940) Growth and Development of the Dental Arches in Children. *The Journal of the American Dental Association*, **27**, 1250–1260. https://doi.org/10.14219/jada.archive.1940.0262

Coughlin JW, Christensen GJ (1966) Growth and calcification in the prenatal human primary molars. *Journal of Dental Research*, **45**, 1541–1547. https://doi.org/10.1177/00220345660450054501

Crawford SEE, Hadley DM, Shepherd G (Eds.) (2018) *The Oxford handbook of the archaeology of childhood*. Oxford, Etats-Unis d'Amérique, Royaume-Uni de Grande-Bretagne et d'Irlande du Nord.

Crowder K, Montgomery J, Gröcke D, Filipek K (2019) Childhood "stress" and stable isotope life-histories in Transylvania. *International Journal of Osteoarchaeology*, **29**. https://doi.org/10.1002/oa.2760

Cunningham C, Scheuer L, Black SM (2016) *Developmental juvenile osteology*.Second edition. Elsevier/AP, Academic Press is an imprint of Elsevier, Amsterdam. https://doi.org/10.1016/b978-0-12-382106-5.05001-5

Czermak A, Fernández-Crespo T, Ditchfield PW, Lee-Thorp JA (2020) A guide for an anatomically sensitive dentine microsampling and age-alignment approach for human teeth isotopic sequences. *American Journal of Physical Anthropology*, **173**, 776–783. https://doi.org/10.1002/ajpa.24126

Dahlberg G, Bernhard Maunsbach A (1948) The eruption of the permanent teeth in the normal population of Sweden. *Acta genetica et statistica medica*, 77–91.

Dahlberg AA, Menegaz-Bock RM (1958) Emergence of the permanent teeth in Pima Indian children: a critical analysis of method and an estimate of population parameters. *Journal of Dental Research*, **37**, 1123–1140. https://doi.org/10.1177/00220345580370061201

Das JK, Salam RA, Thornburg KL, Prentice AM, Campisi S, Lassi ZS, Koletzko B, Bhutta ZA (2017) Nutrition in adolescents: physiology, metabolism, and nutritional needs. *Annals of the New York Academy of Sciences*, **1393**, 21–33. https://doi.org/10.1111/nyas.13330

Dedet B (2008) *Les enfants dans la société protohistorique. L'exemple du Sud de la France.* École Française de Rome.

Demirjian A, Goldstein H, Tanner JM (1973) A new system of dental age assessment. *Human Biology*, **45**, 211–227.

Demirjian A, Levesque GY (1980) Sexual differences in dental development and prediction of emergence. *Journal of Dental Research*, **59**, 1110–1122. https://doi.org/10.1177/00220345800590070301

Demisch A, Wartmann P (1956) Calcification of the mandibular third molar and its relation to skeletal and chronological age in children. *Child Development*, **27**, 459–473. https://doi.org/10.1111/j.1467-8624.1956.tb04824.x

DeNiro MJ (1985) Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature*, **317**, 806–809. https://doi.org/10.1038/317806a0

Dodge Y (2007) *Statistique: dictionnaire encyclopédique*. Springer, Paris Berlin Heidelberg [etc.].

Eerkens JW, Berget AG, Bartelink EJ (2011) Estimating weaning and early childhood diet from serial micro-samples of dentin collagen. *Journal of Archaeological Science*, **38**, 3101–3111. https://doi.org/10.1016/j.jas.2011.07.010

Ellison PT (1995) Breastfeeding, Fertility, and Maternal Condition. In: *Breastfeeding* (ed Stuart-Macadam P), p. 42. Routledge.

Falkner F, Tanner J.M. (1978) *Human Growth: 2 Postnatal Growth*. Kluwer Academic/Plenum Publishers, New York.

Fanning EA (1961) A longitudinal study of tooth formation and root resorption. *The New Zealand Dental Journal*, **104**, 60–61.

Fernández-Crespo T, Czermak A, Lee-Thorp JA, Schulting RJ (2018) Infant and childhood diet at the passage tomb of Alto de la Huesera (north-central Iberia) from bone collagen and sequential dentine isotope composition. *International Journal of Osteoarchaeology*, **28**, 542–551. https://doi.org/10.1002/oa.2659

Feuillâtre C, Beaumont J, Elamin F (2022) Reproductive life histories: can incremental dentine isotope analysis identify pubertal growth, pregnancy and lactation? *Annals of Human Biology*, **49**, 171–191. https://doi.org/10.1080/03014460.2022.2091795

Ganiatsou E, Georgiadou A, Souleles A, Aidonis A, Protopsalti T, Tzevreni S, Konstantinidou K, Vasileiadou S, Siegmund F, Papageorgopoulou C (2023a) Application of machine learning on isotopic data from tooth microsections for reconstructing weaning patterns and physiological stress. *Journal of Archaeological Science: Reports*, **47**, 103765. https://doi.org/10.1016/j.jasrep.2022.103765

Ganiatsou E, Souleles A, Papageorgopoulou C (2023b) WEaning Age FiNder (WEAN): a tool for estimating weaning age from stable isotope ratios of dentinal collagen. *Archaeological and Anthropological Sciences*, **15**, 50. https://doi.org/10.1007/s12520-023-01741-4

García-Mancuso R, Salceda SA (2014) Evaluación de diferentes métodos de estimación de edad por desarrollo de la dentición en restos humanos esqueletizados de entre 0 y 6 meses. *Revista Española de Medicina Legal*, **40**, 133–138. https://doi.org/10.1016/j.reml.2013.12.001

Georgopoulos N, Markou K, Theodoropoulou A, Paraskevopoulou P, Varaki L, Kazantzi Z, Leglise M, Vagenakis AG (1999) Growth and Pubertal Development in Elite Female Rhythmic Gymnasts. *The Journal of Clinical Endocrinology & Metabolism*, **84**, 4525–4530. https://doi.org/10.1210/jcem.84.12.6177

Gilster J, Smith F, Wallace GK (1964) Calcification of Mandibular Second Primary Molars in Relation to Age. *Journal of Dentistry for Children*, **31**, 284–288.

Gödény E (1955) Die typische Zahnformel zu verschiedenen Zeiten während der Wechselgebißperiode. *Z. Altersforsch.*, **8**, 284.

Goude G, Dori I, Sparacello VS, Starnini E, Varalli A (2020a) Multi-proxy stable isotope analyses of dentine microsections reveal diachronic changes in life history adaptations, mobility, and tuberculosis-induced wasting in prehistoric Liguria (Finale Ligure, Italy, northwestern Mediterranean). *International Journal of Paleopathology*, **28**, 99–111. https://doi.org/10.1016/j.ijpp.2019.12.007

Goude G, Salazar-García DC, Power RC, Rivollat M, Gourichon L, Deguilloux M-F, Pemonge M-H, Bouby L, Binder D (2020b) New insights on Neolithic food and mobility patterns in Mediterranean coastal populations. *American Journal of Physical Anthropology*, **173**, 218–235. https://doi.org/10.1002/ajpa.24089

Goude G, Schmitt A, Herrscher E, Loison G, Cabut S, André G (2013) Pratiques alimentaires au Néolithique moyen : nouvelles données sur le site de Pontcharaud 2 (Puy-de-Dôme, Auvergne, France). *Bulletin de la Société préhistorique française*, **110**, 299–317.

Goude G, Villotte S, Salazar-García DC, Rivollat M, Arzelier A, Pemonge M-H, Deguilloux M-F, Schmitt A (2025) Multiproxy evidence highlights exceptional heterogeneous social status in the middle neolithic in Europe. *Archaeological and Anthropological Sciences*, **17**, 224. https://doi.org/10.1007/s12520-025-02321-4

Griffith JI, James HF, Ordoño J, Fernández-Crespo T, Gerritzen CT, Cheung C, Spros R, Claeys P, Goderis S, Veselka B, Snoeck C (2025) Reconstructing prehistoric lifeways using multi-Isotope analyses of human enamel, dentine, and bone from Legaire Sur, Spain. *PLOS ONE*, **20**, e0316387. https://doi.org/10.1371/journal.pone.0316387

Guo Y, Shen H, Xiao P, Xiong D-H, Yang T-L, Guo Y-F, Long J-R, Recker RR, Deng H-W (2006) Genomewide Linkage Scan for Quantitative Trait Loci Underlying Variation in Age at Menarche. *The Journal of Clinical Endocrinology & Metabolism*, **91**, 1009–1014. https://doi.org/10.1210/jc.2005-2179

Gustafson G, Koch G (1974) Age estimation up to 16 years of age based on dental development. *Odontologisk Revy*, **25**, 297–306.

Haavikko K (1970) The formation and the alveolar and clinical eruption of the permanent teeth. An orthopantomographic study. *Suomen Hammaslaakariseuran Toimituksia = Finska Tandlakarsallskapets Forhandlingar*, **66**, 103–170.

Hägg U, Taranger J (1985) Dental development, dental age and tooth counts. *The Angle orthodontist*, **55**, 93–107.

Harris EF (2018) Primary Tooth Mineralization and Exfoliation Ages Calculated from the Moorrees-Fanning-Hunt Study. *Dental Anthropology Journal*, **23**, 61–65. https://doi.org/10.26575/daj.v23i2.77

Harris EF, Buck AL (2018) Tooth Mineralization: A Technical Note on the Moorrees-Fanning-Hunt Standards. *Dental Anthropology Journal*, **16**, 15–20. https://doi.org/10.26575/daj.v16i1.165

Hastie T, Tibshirani R (1986) Generalized Additive Models. *Statistical Science*, **1**, 297–310. https://doi.org/10.1214/ss/1177013604

Herrscher E, Séguy I (2019) *Premiers cris, premières nourritures*. Presses universitaires de Provence, Aix-en-Provence, France.

Hillson S (2005) *Teeth*. Cambridge, Royaume-Uni de Grande-Bretagne et d'Irlande du Nord, Etats-Unis d'Amérique.

Hobson KA, Alisauskas RT, Clark RG (1993) Stable-Nitrogen Isotope Enrichment in Avian Tissues Due to Fasting and Nutritional Stress: Implications for Isotopic Analyses of Diet. *The Condor*, **95**, 388–394. https://doi.org/10.2307/1369361

Huen K, Leung S, Lau J, Cheung A, Leung N, Chiu M (1997) Secular trend in the sexual maturation of Southern Chinese girls. *Acta Paediatrica*, **86**, 1121–1124. https://doi.org/10.1111/j.1651-2227.1997.tb14820.x

Hurme VO (1948) Standards of Variation in the Eruption of the First Six Permanent Teeth. *Child Development*, **19**, 213–231. https://doi.org/10.2307/1125669

Kahl B, Schwarze CW (1988) [Updating of the dentition tables of I. Schour and M. Massler of 1941]. *Fortschritte Der Kieferorthopadie*, **49**, 432–443. https://doi.org/10.1007/BF02341233

Klein H, Palmer CE, Kramer M (1937) Studies on dental caries. 2. The use of the normal probability carve for expressing the age distribution of eruption of the permanent teeth. *Growth*, **1**, 385–394. https://doi.org/10.2307/1125573

van Klinken GJ (1999) Bone Collagen Quality Indicators for Palaeodietary and Radiocarbon Measurements. *Journal of Archaeological Science*, **26**, 687–695. https://doi.org/10.1006/jasc.1998.0385

Kranz PP (1946) *Klinische Zahnheilkunde und ihre Grenzgebiete*. Carl Hanser, München.

Kraus BS (1959) Calcification of the human deciduous teeth. *Journal of the American Dental Association (1939)*, **59**, 1128–1136. https://doi.org/10.14219/jada.archive.1959.0272

Krstevska-Konstantinova M, Charlier C, Craen M, Du Caju M, Heinrichs C, de Beaufort C, Plomteux G, Bourguignon J p. (2001) Sexual precocity after immigration from developing countries to Belgium: evidence of previous exposure to organochlorine pesticides. *APMIS*, **109**, S135–S143. https://doi.org/10.1111/j.1600-0463.2001.tb05759.x

Kurle CM, Koch PL, Tershy BR, Croll DA (2014) The effects of sex, tissue type, and dietary components on stable isotope discrimination factors (Δ^{13} C and Δ^{15} N) in mammalian omnivores. *Isotopes in Environmental and Health Studies*, **50**, 307–321. https://doi.org/10.1080/10256016.2014.908872

Le Roy M (2015) Les enfants au Néolithique : du contexte funéraire à l'interprétation socioculturelle en France de 5700 à 2100 avant J.-C. phdthesis Thesis. Université de Bordeaux.

Le Roy M (2022) Pratiques funéraires et recrutement : reprise d'étude des collections osseuses issues des dolmens du Languedoc oriental et sud des Cévennes à la fin du Néolithique. *L'Anthropologie*, **126**, 103099. https://doi.org/10.1016/j.anthro.2022.103099

Le Roy M, Rottier S, Tillier A (2018) Who was a 'Child' During the Neolithic in France? *Childhood in the Past*, **11**. https://doi.org/10.1080/17585716.2018.1495141

Lee JM, Appugliese D, Kaciroti N, Corwyn RF, Bradley RH, Lumeng JC (2007) Weight Status in Young Girls and the Onset of Puberty. *Pediatrics*, **119**, e624–e630. https://doi.org/10.1542/peds.2006-2188

Leggett S (Ed.) (2025) Recommendation of: Isobiography of the first farmers: effects of age-estimating referential and statistical models on reconstructing infant life. Round#2. *Peer Community in Archaeology*, archaeo.100609. https://doi.org/10.24072/pci.archaeo.100609

Letterlé F (2021) *Du Néolithique final à l'âge du Bronze moyen en région Auvergne-Rhône-Alpes, Projet collectif de recherches, programme 2020-2022, rapport intermédiaire de 2020*. Service régional de l'archéologie Auvergne.

Lewis M (2018) *Paleopathology of children: identification of pathological conditions in the human skeletal remains of non-adults*. Elsevier/AP, Academic Press, an imprint of Elsevier, London, United Kingdom.

Lew-Levy S, Reckin R, Lavi N, Cristóbal-Azkarate J, Ellis-Davies K (2017) How Do Hunter-Gatherer Children Learn Subsistence Skills? : A Meta-Ethnographic Review. *Human Nature (Hawthorne, N.Y.)*, **28**, 367–394. https://doi.org/10.1007/s12110-017-9302-2

Lillehammer G (1989) A child is born. The child's world in an archaeological perspective. *Norwegian Archaeological Review*, **22**, 89–105. https://doi.org/10.1080/00293652.1989.9965496

Liversidge H (2003) Variation in modern human dental development. In: *Patterns of Growth and Development in the Genus Homo* Cambridge Studies in Biological and Evolutionary Anthropology. (eds Thompson JL, Krovitz GE, Nelson AJ), pp. 73–113. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511542565.004

Liversidge HM, Smith BH, Maber M (2010) Bias and accuracy of age estimation using developing teeth in 946 children. *American Journal of Physical Anthropology*, **143**, 545–554. https://doi.org/10.1002/ajpa.21349

Liversidge HM, Speechly T (2001) Growth of permanent mandibular teeth of British children aged 4 to 9 years. *Annals of Human Biology*, **28**, 256–262. https://doi.org/10.1080/030144601300119070

Logan WHG, Kronfeld R (1933) Development of the Human Jaws and Surrounding Structures from Birth to the Age of Fifteen Years*. *The Journal of the American Dental Association (1922)*, **20**, 379–428. https://doi.org/10.14219/jada.archive.1933.0080

Loison G, Gisclon J-L, par Gilles Loison (1991) La Nécropole de Poncharaud 2 dans le cadre de nouvelles approches du peuplement néolithique de la Basse-Auvergne. In: *Identité du Chasséen, Actes du colloque international de Nemours 1989* Mémoires du Musée de préhistoire d'Ile-de-France., pp. 399–408. Nemours.

Lovejoy CO (1985) Dental wear in the Libben population: Its functional pattern and role in the determination of adult skeletal age at death. *American Journal of Physical Anthropology*, **68**, 47–56. https://doi.org/10.1002/ajpa.1330680105

Lunt RC, Law DB (1974) A review of the chronology of calcification of deciduous teeth. *The Journal of the American Dental Association*, **89**, 599–606. https://doi.org/10.14219/jada.archive.1974.0446

Lysell L, Magnusson B, Thilander B (1964) Eruption of the deciduous teeth as regards time and order. *Int Dent J*, **14**, 330–342.

Masset C (1982) Estimation de l'âge au décès par les sutures crâniennes. Sciences naturelles : Université Paris VII, Paris.

Mays S, Gowland R, Halcrow S, Murphy E (2017) Child Bioarchaeology: Perspectives on the Past 10 Years. *Childhood in the Past*, **10**, 38–56. https://doi.org/10.1080/17585716.2017.1301066

Mekota A-M, Grupe G, Ufer S, Cuntz U (2006) Serial analysis of stable nitrogen and carbon isotopes in hair: monitoring starvation and recovery phases of patients suffering from anorexia nervosa. *Rapid communications in mass spectrometry: RCM*, **20**, 1604–1610. https://doi.org/10.1002/rcm.2477

Meredith HV (1946) Order and Age of Eruption for the Deciduous Dentition. *Journal of Dental Research*, **25**, 43–66. https://doi.org/10.1177/00220345460250010901

Moorrees CFA (1965) Normal Variation in Dental Development Determined with Reference to Tooth Eruption Status. *Journal of Dental Research*, **44**, SUPPL:161-173. https://doi.org/10.1177/00220345650440011301

Moorrees CFA, Fanning EA, Hunt EE (1963a) Age Variation of Formation Stages for Ten Permanent Teeth. *Journal of Dental Research*, **42**, 1490–1502. https://doi.org/10.1177/00220345630420062701

Moorrees CFA, Fanning EA, Hunt Jr. EE (1963b) Formation and resorption of three deciduous teeth in children. *American Journal of Physical Anthropology*, **21**, 205–213. https://doi.org/10.1002/ajpa.1330210212

Moyers RE (1963) Handbook of Orthodontics. B. Development of the dentition and occlusion. The Year Book Medical Publishers. *Inc., Chicago*, **51**.

Murail P, Brůžek J, Houët F, Cunha E (2005) DSP: a tool for probabilistic sex diagnosis using worldwide variability in hip-bone measurements. *Bulletins et Mémoires de la Société d'Anthropologie de Paris*, 167–176. https://doi.org/10.4000/bmsap.1157

Murphy EM (2017) Atypical burial practice and juvenile age-at-death in later medieval Gaelic Ireland: The evidence from Ballyhanna, Co. Donegal. *Children, death and burial: archaeological discourses. Oxford: Oxbow Books*, 227–248.

Murphy EM, Le Roy M (Eds.) (2017) *Children, death and burial: archaeological discourses*. Oxbow Books, Oxford ; Philadelphia.

Nehlich O (2015) The application of sulphur isotope analyses in archaeological research: A review. *Earth-Science Reviews*, **142**, 1–17. https://doi.org/10.1016/j.earscirev.2014.12.002

Neuberger FM, Jopp E, Graw M, Püschel K, Grupe G (2013) Signs of malnutrition and starvation—Reconstruction of nutritional life histories by serial isotopic analyses of hair. *Forensic Science International*, **226**, 22–32. https://doi.org/10.1016/j.forsciint.2012.10.037

Nolla CM (1960) The development of the permanent teeth. *Journal of Dentistry for Children*.

Orban BJ (1957) *Oral histology and embryology*. Mosby, Michigan, United States of America.

Parent A-S, Teilmann G, Juul A, Skakkebaek NE, Toppari J, Bourguignon J-P (2003) The Timing of Normal Puberty and the Age Limits of Sexual Precocity: Variations around the World, Secular Trends, and Changes after Migration. *Endocrine Reviews*, **24**, 668–693. https://doi.org/10.1210/er.2002-0019

R core Team (2024) R: a language and environment for statistical computing. r foundation for statistical computing.

Ramirez Rozzi F (2016) Diversity in tooth eruption and life history in humans: illustration from a Pygmy population. *Scientific Reports*, **6**, 27405. https://doi.org/10.1038/srep27405

Reid DJ, Dean MC (2006) Variation in modern human enamel formation times. *Journal of Human Evolution*, **50**, 329–346. https://doi.org/10.1016/j.jhevol.2005.09.003

Rey L, Rottier S, Santos F, Goude G (2021) Sex and age-related social organization in the Neolithic: A promising survey from the Paris Basin. *Journal of Archaeological Science: Reports*, **38**, 103092. https://doi.org/10.1016/j.jasrep.2021.103092

Rivollat M, Rohrlach AB, Ringbauer H, Childebayeva A, Mendisco F, Barquera R, Szolek A, Le Roy M, Colleran H, Tuke J, Aron F, Pemonge M-H, Späth E, Télouk P, Rey L, Goude G, Balter V, Krause J, Rottier S, Deguilloux M-F, Haak W (2023) Extensive pedigrees reveal the social organization of a Neolithic community. *Nature*, **620**, 600–606. https://doi.org/10.1038/s41586-023-06350-8

Robinow M, Richards TW, Anderson M (1942) The eruption of deciduous teeth. *Growth*, **6**, 127–133.

Röse C (1909) Über die mittlere Durchbruchszeit der bleibenden Zähne des Menschen. *Dtsch Monatsschr Zahnheilkd*, **27**, 553–570.

Rothenbuhler A, Fradin D, Heath S, Lefevre H, Bouvattier C, Lathrop M, Bougnères P (2006) Weight-Adjusted Genome Scan Analysis for Mapping Quantitative Trait Loci for Menarchal Age. *The Journal of Clinical Endocrinology & Metabolism*, **91**, 3534–3537. https://doi.org/10.1210/jc.2006-0150

Sayle KL, Brodie CR, Cook GT, Hamilton WD (2019) Sequential measurement of δ15N, δ13C and δ34S values in archaeological bone collagen at the Scottish Universities Environmental Research Centre (SUERC): A new analytical frontier. *Rapid Communications in Mass Spectrometry*, **33**, 1258–1266. https://doi.org/10.1002/rcm.8462

Scharlotta I, Goude G, Herrscher E, Bazaliiskii VI, Weber AW (2018) “Mind the gap”—Assessing methods for aligning age determination and growth rate in multi-molar sequences of dietary isotopic data. *American Journal of Human Biology*, **30**, e23163. https://doi.org/10.1002/ajhb.23163

Schmitt A (2005) Une nouvelle méthode pour estimer l'âge au décès des adultes à partir de la surface sacro-pelvienne iliaque. *Bulletins et Mémoires de la Société d'Anthropologie de Paris*, 89–101. https://doi.org/10.4000/bmsap.943

Schour I, Massler M, Poncher HG (1941) Developmental pattern of the child as reflected in the calcification pattern of the teeth. *American Journal of Diseases of Children*, **62**, 33–67. https://doi.org/10.1001/archpedi.1941.02000130042004

Simpson SW, Kunos CA (1998) A radiographic study of the development of the human mandibular dentition. *Journal of Human Evolution*, **35**, 479–505. https://doi.org/10.1006/jhev.1998.0235

Sjöberg C (1961) Mjölktandsgenombrott. *Svensk tandläk*, **54**.

Sloboda DM, Hart R, Doherty DA, Pennell CE, Hickey M (2007) Age at Menarche: Influences of Prenatal and Postnatal Growth. *The Journal of Clinical Endocrinology & Metabolism*, **92**, 46–50. https://doi.org/10.1210/jc.2006-1378

Smith BH (1991) Standards of human tooth formation and dental age assessment. In: *Advances in Dental Anthropology* (eds Kelley MA, Larsen CS), pp. 143–168. Wiley-Liss Inc., New York.

Smith TM (2013) Teeth and Human Life-History Evolution*. *Annual Review of Anthropology*, **42**, 191–208. https://doi.org/10.1146/annurev-anthro-092412-155550

Sousa AM da S, Jacometti V, AlQahtani S, Silva RHA da (2020) Age estimation of Brazilian individuals using the London Atlas. *Archives of Oral Biology*, **113**, 104705. https://doi.org/10.1016/j.archoralbio.2020.104705

Stark O, Peckham CS, Moynihan C (1989) Weight and age at menarche. *Archives of Disease in Childhood*, **64**, 383–387. https://doi.org/10.1136/adc.64.3.383

Steggerda M, Hill TJ (1942) Eruption time of teeth among Whites, Negroes, and Indians. *American Journal of Orthodontics and Oral Surgery*, **28**, 361–370. https://doi.org/10.1016/S0096-6347(42)90608-2

Stones HH, Lawton FE, Bransby ER, Hartley HO (1951) Time of eruption of permanent teeth and time of shedding of deciduous teeth. *British Dental Journal*, **90**, 1–7.

Sundick RI (1978) Human Skeletal Growth and Age Determination. *Human Skeletal Growth and Age Determination*, **29**, 228–249. https://doi.org/10.1520/jfs10377j

Tegzes E (1959) Der Zeitablauf der Eruption des Milchgebisses. *ACTA PAEDIATRICA*, **1**, 289–300.

Teilmann G, Pedersen CB, Skakkebæk NE, Jensen TK (2006) Increased Risk of Precocious Puberty in Internationally Adopted Children in Denmark. *Pediatrics*, **118**, e391–e399. https://doi.org/10.1542/peds.2005-2939

Theintz GE, Howald H, Allemann Y, Sizonenko PC (1989) Growth and pubertal development of young female gymnasts and swimmers: a correlation with parental data. *International Journal of Sports Medicine*, **10**, 87–91. https://doi.org/10.1055/s-2007-1024880

Tillier A-M (1995) Paléoanthropologie et pratiques funéraires au Levant méditerranéen durant le Paléolithique moyen : le cas des sujets non-adultes. *Paléorient*, **21**, 63–76. https://doi.org/10.3406/paleo.1995.4618

Tony L. S, H Maness, A AD, Ef H (2016) A Comparison of Two Dental Age Estimation Techniques in Contemporary American Whites: The Moorrees and Demirjian Approaches. *International Journal of Forensic Science & Pathology*, 243–248. https://doi.org/10.19070/2332-287X-1600058

Ubelaker DH (1978) *Human skeletal remains : excavation, analysis, interpretation*. Chicago : Aldine Pub. Co.

Van Der Haas VM, Garvie-Lok S, Bazaliiskii VI, Weber AW (2018) Evaluating sodium hydroxide usage for stable isotope analysis of prehistoric human tooth dentine. *Journal of Archaeological Science: Reports*, **20**, 80–86. https://doi.org/10.1016/j.jasrep.2018.04.013

Van Gennep A (1901) *Les Rites de passage, étude systématique des rites de la porte et du seuil, de l'hospitalité, de l'adoption, de la grossesse et de l'accouchement, de la naissance, de l'enfance, de la puberté, de l'initiation, de l'ordination, du couronnement, des fiançailles et du mariage, des funérailles, des saisons, etc.* É. Nourry, Paris.

Vila-Blanco N, Varas-Quintana P, Tomás I, Carreira MJ (2023) A systematic overview of dental methods for age assessment in living individuals: from traditional to artificial intelligence-based approaches. *International Journal of Legal Medicine*, **137**, 1117–1146. https://doi.org/10.1007/s00414-023-02960-z

Wang Y (2002) Is Obesity Associated With Early Sexual Maturation? A Comparison of the Association in American Boys Versus Girls. *Pediatrics*, **110**, 903–910. https://doi.org/10.1542/peds.110.5.903

Waters-Rist A (2019) Breastfeeding and Weaning Practices in Ancient Siberian Foragers : Stable Isotope Reconstruction. In: *Premiers cris, premières nourritures* Corps et âmes. (eds Herrscher E, Séguy I), pp. 277–286. Presses universitaires de Provence, Aix-en-Provence. https://doi.org/10.4000/books.pup.34598

Willems G, Van Olmen A, Spiessens B, Carels C (2001) Dental age estimation in Belgian children: Demirjian's technique revisited. *Journal of Forensic Sciences*, **46**, 893–895.

Wood SN (2011) Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*, **73**, 3–36. https://doi.org/10.1111/j.1467-9868.2010.00749.x

Wood SN (2017) *Generalized Additive Models: An Introduction with R, Second Edition*. Chapman and Hall/CRC, New York. https://doi.org/10.1201/9781315370279

Zazzo A, Balasse M, Passey BH, Moloney AP, Monahan FJ, Schmidt O (2010) The isotope record of short- and long-term dietary changes in sheep tooth enamel: Implications for quantitative reconstruction of paleodiets. *Geochimica et Cosmochimica Acta*, **74**, 3571–3586. https://doi.org/10.1016/j.gca.2010.03.017

Zhao J, Ding L, Li R (1990) [Study of dental maturity in children aged 3-16 years in Chengdu]. *Hua Xi Yi Ke Da Xue Xue Bao = Journal of West China University of Medical Sciences = Huaxi Yike Daxue Xuebao*, **21**, 242–246.

Zhou Y, Zhu W, Guo Z, Zhao Y, Song Z, Xiao J (2007) Effects of maternal nuclear genome on the timing of puberty in mice offspring. *The Journal of Endocrinology*, **193**, 405–412. https://doi.org/10.1677/joe.1.07049