Childhood mobility revealed by strontium isotope analysis: a review of the multiple tooth sampling approach

Hrncir, V.; Laffoon, J.E.

Archaeological and Anthropological Sciences (2019) 11:5301–5316
https://doi.org/10.1007/s12520-019-00868-7

ORIGINAL PAPER

Childhood mobility revealed by strontium isotope analysis: a review of the multiple tooth sampling approach

Václav Hrnčíř[1,2] · Jason E. Laffoon[3]

Received: 6 December 2018 / Accepted: 15 May 2019 / Published online: 20 June 2019

Abstract
Strontium isotope analysis of archeological skeletal materials is a highly effective and commonly employed analytical tool to investigate past human mobility and migration. Most such studies to date have focused on the analysis of a single tooth sample per individual to identify migration. Increasingly, however, studies have analyzed multiple teeth from the same individual permitting the detection of migrations occurring during childhood, more fine-grained temporal resolution of the age at which migration(s) occurred, and even the identification of multiple migration episodes. In this study, we review the application of such approaches to a wide range of archeological contexts worldwide. We compiled and analyzed published $^{87}Sr/^{86}Sr$ data for 1043 individuals from 122 sites to explore the potential variability of childhood mobility patterns cross-culturally. The results demonstrate a high degree of variability in childhood mobility that differs significantly between different regions and time periods. Potential interpretations involved in multiple tooth $^{87}Sr/^{86}Sr$ analysis are reviewed, including heterogeneity in variance of regional $^{87}Sr/^{86}Sr$, as well as variability in human mobility patterns such as residential change of whole family, fosterage, herding activities, post-marital residence rules, or forced migrations. Various limitations and caveats concerning the multiple teeth sampling approach are also critically discussed.

Keywords Childhood · Mobility · Migration · Strontium isotope · Cross-cultural comparison

Introduction

The topic of human mobility is not only popular in discussions of contemporary societies but owing to the rapid development of various scientific approaches, such as genetics and biogeochemical analyses, also in archeological research. Traditional archeological methods to explore past human mobility often relied upon indirect evidence such as the changing distributions of material culture in time and space. However, it has long been recognized that it is extremely difficult to distinguish between the actual movement of people and other processes such as diffusion (the movement of ideas), exchange and trade (the movement of objects and materials), independent innovation and evolution (the autochthonous development of similar ideas and cultural "traits"), or emulation (the copying of behaviors) (Anthony 1990; Burmeister 2000, 2016; Hakenbeck 2008; Laffoon 2012).

In the last decades, there has been an exponential increase in archeological research utilizing recent advances in scientific methods and techniques. The trend, sometimes called *The Third Science Revolution in Archeology* (Kristiansen 2014), began with the study of genetic and phenotypic data (e.g., Ammerman and Cavalli-Sforza 1984) and increasingly the use of biogeochemical analyses based on the study of the isotope compositions (e.g., strontium, oxygen, and lead) of biological tissues (Brown and Brown 2011; Laffoon et al. 2017; Slovak and Paytan 2011). These methods, unlike traditional archeological approaches, can provide direct evidence about the movement of populations and individuals from the analyses of their skeletal and non-skeletal remains.

To date, most such studies have focused on the analysis of a single tooth sample per individual to identify migration. The

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12520-019-00868-7) contains supplementary material, which is available to authorized users.

✉ Václav Hrnčíř
hrncir.vaclav@gmail.com

1 Department of Archaeology, Faculty of Arts, Charles University, Celetná 20, 116 42 Prague, Czech Republic

2 Institute of Archaeology of the Czech Academy of Sciences, Prague, Letenska 4, 118 01 Prague, Czech Republic

3 Faculty of Archaeology, Leiden University, Einsteinweg 2, 2333CC Leiden, The Netherlands

single tooth sampling approach is, however, limited to the identification of a single migration event occurring sometime after the formation of the sampled tooth (varying from roughly birth to mid-teens for permanent teeth, depending on the dental element). Increasingly, however, studies have analyzed multiple teeth from the same individual permitting the detection of migrations during childhood, more fine-grained temporal resolution assessments of the age at which migration(s) occurred, and even multiple migration episodes (e.g., Buikstra et al. 2004; Eriksson et al. 2018; Evans et al. 2006; Fraser et al. 2018; Hadley and Hemer 2011; Hedman et al. 2018; Knipper 2009; Knipper et al. 2018; Schweissing and Grupe 2003; Weber and Goriunova 2013). This follows the current trend of increased interest in the topic of childhood in the past, which had been previously neglected (e.g., Crawford et al. 2018; Hadley and Hemer 2014; Murphy 2017).

The objective of the current study is to compile and analyze published $^{87}Sr/^{86}Sr$ data from sites across the world to explore the variability in childhood mobility cross-culturally. We also discuss potential outcomes and interpretations involved in multiple tooth $^{87}Sr/^{86}Sr$ analysis and highlight various issues concerning this approach and their implications for future research.

Background

Strontium isotopes from the ground to the human body

The principles, methods, and applications of strontium isotope analysis in archeological research have been described in detail elsewhere (e.g., Bentley 2006; Slovak and Paytan 2011). Here, we provide only a brief summary.

Strontium (Sr) is a chemical element that occurs in rocks, as well as in seawater, fresh water, soil, plants, and animals, including humans. There are four naturally occurring isotopes (atoms that have the same number of protons, but different numbers of neutrons) of strontium— ^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr. Three of these are stable and non-radiogenic, while ^{87}Sr is radiogenic, being produced by the radioactive decay of ^{87}Rb, with a half-life of approximately 4.88×10^{10} years (Faure and Mensing 2005: 3).

From an archeological point of view, the most important ratio is that of $^{87}Sr/^{86}Sr$ because it varies substantially in regions with different bedrock geology and thus serves as a "geochemical signature." In simple terms, very old rocks have higher $^{87}Sr/^{86}Sr$ ratios, while younger rocks have lower $^{87}Sr/^{86}Sr$ ratios (Bentley 2006: 139). Besides, there are additional, non-geological sources of strontium in the biosphere, such as seawater, groundwater, rivers, or atmospheric aerosols that also influence the resulting $^{87}Sr/^{86}Sr$ signatures in biological tissues, although usually to a lesser extent (Bentley 2006).

Strontium passes from weathered bedrock through soil into the plants and then moves through the food chain into the human body, where it substitutes for calcium in the mineral portions of skeletal tissues. Because of strontium's relatively large atomic mass, $^{87}Sr/^{86}Sr$ ratios change very little as it moves through trophic levels. This means that the strontium ratio measured in human tissues reflects the composition of water, plants, and animals consumed, which in turn reflect the $^{87}Sr/^{86}Sr$ geochemical signatures in a given territory from which consumed food and water originates.

On this basis, it is possible to distinguish individuals who are local (i.e., have $^{87}Sr/^{86}Sr$ ratios in accordance with a local range) and those who are not. Therefore, characterizing the local range of $^{87}Sr/^{86}Sr$ variation is an essential component of such research (Price et al. 2002). Researchers have come up with several approaches to this problem, including using the average Sr ratio of human bones (Grupe et al. 1997; Price et al. 2001); a "normalized" sample of human tooth enamel ratios (Wright 2005); modern environmental samples (rocks, soil, water, and plants) which were collected around a site (Evans et al. 2010; Hodell et al. 2004); or archeological faunal samples such as rodents, land snails, and other small animals that presumably lived locally (Bentley 2006; Hedman et al. 2009; Price et al. 2002). The use of archeological fauna to determine strontium isotope baselines is not possible for all regions due to the unavailability of appropriate samples, large investments in time and resources, or in cases of high proportions of marine foods in paleodiet (Slovak and Paytan 2011: 745–746), and the appropriateness of an exclusive focus on faunal isotopic data has been questioned (Grimstead et al. 2017).

Different tissues form at different time periods and remodel at varying rates (Eriksson 2013: 134–135). Tooth enamel and (primary) dentine form primarily during infancy and childhood, after which their chemical composition does not generally change, while bones remodel continuously. Hair and nails are metabolically inert once formed but grow progressively during the whole lifespan. Theoretically, analysis of different types of tissues from the same individual may indicate dietary changes over time, which in turn may indicate residential change. Practically, however, most researchers focus exclusively on tooth enamel because archeological bones are susceptible to diagenetic contamination (Bentley 2006: 163–169; Hoppe et al. 2003) and non-skeletal tissues are usually not preserved. Nevertheless, by analyzing two or more teeth per individual (e.g., first molars versus third molars), it is possible to demonstrate mobility during childhood and/or adolescence.

Nevertheless, it is worth stressing that the strontium isotope approach has multiple limitations, one of the most important of which is equifinality (Price et al. 2007). This means that it is not possible, at least with a single isotope proxy and in the absence of other evidence, to identify migrations that have occurred within an isotopically homogenous area nor those that occurred between two geographically distinct but isotopically similar locations. Consequently, the non-locals, identified by the strontium isotope method, should be considered a minimal estimate of the actual number of non-locals within any given analyzed sample population. This limitation is not, however, specific to the multiple tooth sampling approach to strontium isotope analysis, as it is equally true of all single isotope proxy approaches.

Strontium isotopes as evidence for mobility during childhood

While strontium ratios in teeth reflect the places of residence during different childhood ages, the ratios in the bones, on the contrary, correspond to the last years, and in the case of nails and hair even the last months of life. For instance, comparison of the strontium ratios in different bones and teeth confirmed the high mobility of the famous Alpine Iceman "Ötzi" (Hoogewerff et al. 2001; Müller et al. 2003). Similarly, high temporal resolution reconstructions of mobility of extremely well-preserved individuals from Denmark were revealed through the combined analysis of their teeth, nails, and hair (Frei et al. 2015a, 2015b, 2017).

Due to the low resistance to contamination in the case of bones, and the very rare preservation in the case of hair and nails, however, the most common analyzed material is dental enamel. One of these approaches is micro-sampling of a single tooth (or intra-tooth sequential sampling) at the resolution of its enamel growth layers by laser ablation or micro-drilling (Copeland et al. 2008; Lewis et al. 2014; Richards et al. 2008). The advantages of this sampling method are the possibility to explore individual mobility at smaller temporal scales and the minimal destruction of precious archeological materials. Unfortunately, it is still not clear whether this method is sufficiently reliable, and whether the mineralization of these layers occurs in a well-ordered linear sequential fashion in humans or rather in a non-linear multidirectional pattern (Montgomery and Evans 2006; Montgomery et al. 2010; Nowell and Horstwood 2009). For this reason, the most common method to explore human childhood mobility is currently bulk isotopic analysis of different teeth from the same individual.

Tooth enamel forms in the early years of human life and is not remodeled afterwards (Hillson 1996). Moreover, the age of formation of different teeth is variable per tooth type (element) and is relatively consistent within and between populations. For example, deciduous teeth mineralize approximately between the prenatal period and 1st year after birth, first molars from ca. birth to 3rd year, second molars and premolars between roughly the 3rd and 8th years, and third molars between approximately the 8th and 14th years of age (AlQahtani et al. 2010). Differences in strontium isotope ratios between teeth formed at different ages can therefore be an indication for residential change during childhood or adolescence.

A major unresolved question with such approaches is what difference in $^{87}Sr/^{86}Sr$ ratios between teeth of a given individual is large enough to be clearly identified as resulting from mobility? Since strontium primarily enters the body through dietary sources, and because diets usually vary at different stages of life, whether due to seasonal changes in resource availability or due to changes in eating habits over time, it is likely that the strontium ratios will be slightly different even within the teeth of a person who spent his/her entire life in a single location. Moreover, in isotopically varied landscapes, strontium concentrations may differ widely not only between different food types but also between similar food types with distinct, although nearby, biogeochemical origins (Laffoon 2012: 54). Researchers often mention 0.001 as a minimal offset between the $^{87}Sr/^{86}Sr$ ratios of two different teeth that is significant enough to demonstrate an individual's movement or migration (Knipper et al. 2014: 826; Kootker et al. 2016: 14; Scheeres et al. 2013: 3620; Scheeres et al. 2014: 504; Slater et al. 2014: 124). Unfortunately, a proper justification for this specific cut-off is not usually provided.

The most promising approach to inter-tooth offset determination and its justification was recently proposed by Knipper and colleagues (Knipper et al. 2018). Through analysis of differences in strontium isotope ratios in pairs of deciduous teeth and between a deciduous tooth and a permanent first molar from the same individuals, they concluded that for detection of residential changes at the site of Basel–Gasfabrik in Switzerland, the cut-off value is around 0.00064 or 0.00073. By consequence, offsets lower than this cut-off (among teeth from the same individual) may indicate permanent residence, while larger offsets suggest possible residential change (Knipper et al. 2018: 745).

We attempted to repeat a similar procedure on a larger sample from multiple locations, by comparing intra-individual offsets in $^{87}Sr/^{86}Sr$ ratios among three different types of tooth pairs (from the same individuals): (1) deciduous versus deciduous, (2) deciduous versus permanent first molar, and (3) first molar versus another first molar (Table 1 in Online Resource 1). This sample set contains 49 individuals from 17 sites, including 11 children previously analyzed by Knipper et al. (2018). Our results are in general accordance with theirs. The maximum absolute offset is 0.00077 with an average of 0.00020 ± 0.00022 ($\Delta^{87}Sr/^{86}Sr$ tooth 1 − tooth 2; $n = 49$ pairs, 1 SD). Two standard deviations from the mean of absolute differences are therefore 0.00063. It should be emphasized that the observed differences come from the teeth of individuals reflecting up to ca. 3 years of age. It can be argued that older children may have experienced even more significant changes in their diet and thus even greater differences in their $\Delta^{87}Sr/^{86}Sr$ values even for local or non-mobile individuals and populations. However, this data set is still very small and regionally biased (majority of sites come from Europe), so it would be risky trying to generalize this result for all other sites. As Fig. A1 indicates, the cut-off value could vary considerably from site to site.

In this study, we do not apply a specific cut-off value. Although the proposed value of 0.001 might be conservative enough for use with inter-site comparisons, the current lack of data on intra-individual variation in strontium isotope values does not permit an assessment of its broader validity at this time. On the contrary, we can expect large regional differences due to numerous confounding variables such as differential ranges of local variation, the spatial extent of isotopic homogeneity, variable catchment areas, long-distance food transport, and culturally mediated differences in the sourcing of food resources, just to name a few. More research at multiple scales needs to be done on this topic in the future.

Methods

We compiled human strontium isotope data from studies that were published before April 2018. We focused only on data for tooth enamel and we included only individuals with two or more dental elements which form at different ages. The databases used to find the information for this study was primarily Web of Science, combined with more limited searches on Google Scholar and ResearchGate. Various combinations of the following search terms were used: strontium, Sr, enamel, isotope. On Web of Science, we limited the Research Areas to Anthropology and Archeology. It should be noted that the database created is not exhaustive, but rather is biased toward data published in English and searchable through the mentioned web search tools.

The strontium isotope values were compiled along with ancillary information about the skeletons and sites (Table 2 in Online Resource 1). We created a unique ID for each individual and Site Code for each site purely for analytical purposes. The identification of each individual is possible through the column Burial that we have taken from the original literature. Sex and Age variables were also extracted from the published datasets. Next, we created three tooth categories: (1) Early (including deciduous teeth, incisors, canines, and permanent first molars); (2) Middle (including premolars and permanent second molars); (3) Late (third molars). The Early category corresponds approximately with the ages of 0–3 years, the Middle category with 3–8 years, and the Late category with 8–14 years of age. In case there were more teeth from the same category, we preferred molars because these were more commonly analyzed. In case there were two or more of the same teeth analyzed (e.g., two second molars), we averaged their values (in database labeled with *). Since not all authors use FDI World Dental Federation notation, we labeled teeth in a simplified but consistent manner: I1 = central incisor; I2 = lateral incisor; C = canine; P1 = first premolar; P2 = second premolar; M1 = permanent first molar; M2 = permanent second molar; M3 = third molar; dec. = deciduous tooth. Resulting analyses should not be affected by this simplification since the same teeth types have very similar ages of formation which overlap considerably between different locations in the dental arcade (left/right, mandible/maxilla) (AlQahtani et al. 2010). The ^{87}Sr/^{86}Sr ratios are reported to five decimal places. Offsets between two teeth are presented as follows: ΔL-E = Late tooth–Early tooth; ΔM-E = Middle tooth–Early tooth; ΔL-M = Late tooth–Middle tooth.

Table 3 in Online Resource 1 contains ancillary data for all sites, including summarizing numbers of individuals in the database, references, and assignments to modern countries. In case of six regional case studies (see below) the sites also contain the column Period. This category refers to the dating of the skeletal assemblages and is both relative and approximate due to a lack of absolute data on the one hand and in order to increase the sample size per period on the other. Therefore, the aim of the subsequent analyses is not to identify the exact differences between the periods but rather to indicate the main trends.

Statistical comparisons were performed using IBM SPSS Statistics version 23 for Windows.

Dataset

We collected data for 1043 individuals from 122 sites (Tables 2 and 3 in Online Resource 1). The most common tooth pairs were Early–Late ($n = 700$), followed by Early–Middle (340) and Middle–Late (285), with some individuals represented by multiple pairs. As shown in Fig. 1, the most sites and individuals come from Europe (71 sites and 477 individuals), while other continents are represented less. Twenty-six sites (371 individuals) come from Americas, 22 sites (133 individuals) from Asia, and 3 sites (62 individuals) from Africa. The majority of sites contain 10 or fewer individuals, while the largest sample ($n = 119$) comes from Cahokia, IL, USA. From a chronological perspective, the earliest data come from African site of Gobero (9500 to 8200 cal BP) and Near-East site of Basta (7500–7000 cal BC), while the latest come from colonial era (post-medieval) cemeteries in Cape Town, South Africa and Barbados, West Indies (both 17th–19th centuries AD).

It would be impractical to report and discuss the results for each site. For that reason, we decided to select six regions as archeological case studies based on the size of the associated regional multi-tooth ^{87}Sr/^{86}Sr datasets: (1) Cis-Baikal in Siberia; (2) Southeastern Arabia; (3) Peru; (4) American Midwest; (5) Cape Town in South Africa; (6) Central Europe (Fig. 1). The Central Europe case study contains data for a long temporal span (from 6th millennium BC till 1st

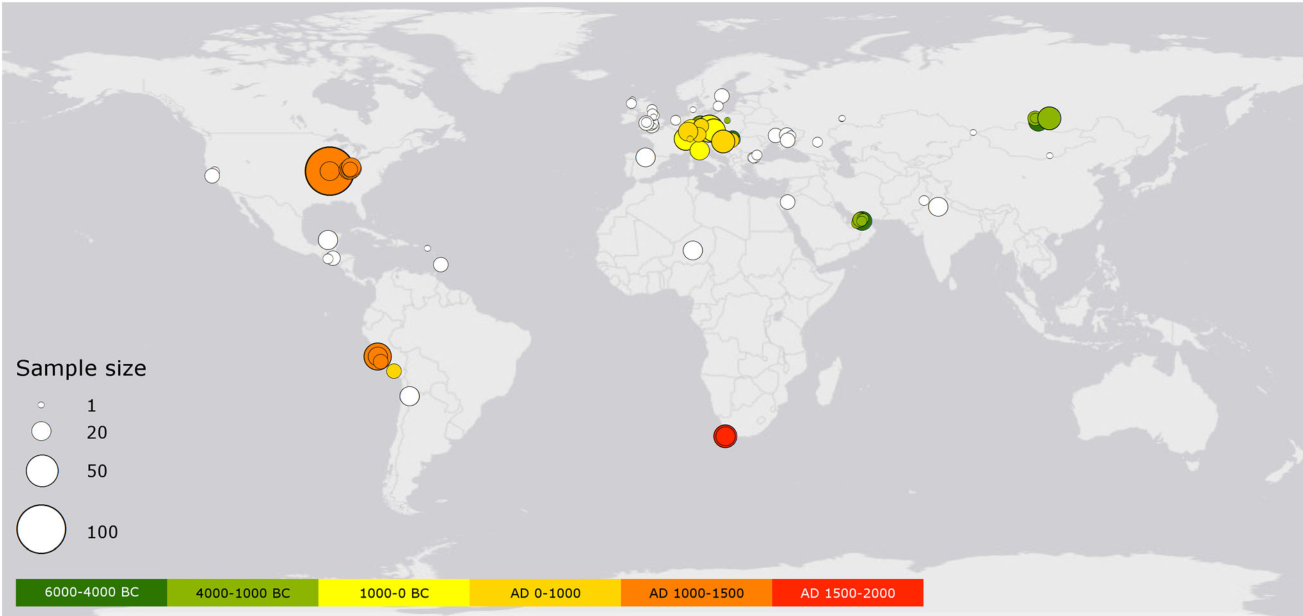

Fig. 1 Map of all sites represented in the dataset. Sites from six regional cases studies are highlighted and categorized by periods

millennium AD) and is additionally divided into different time periods (Fig. 2).

Before presenting the results, we first describe all regions briefly. The first regional case study is Cis-Baikal, Siberia. Multiple strontium isotope signatures were obtained from 54 individuals at three hunter-gatherer cemeteries dating from 8000 to 4000 BP (Haverkort et al. 2008; Haverkort et al. 2010; Weber and Goriunova 2013). Apart from the fact that these are the only forager populations in the database, this sample is remarkable because strontium ratios for all three molars (M1, M2, and M3) are available for most individuals. This allows tracking of differences across three distinct age categories.

The second regional sample consists of 45 individuals from 10 southeastern Arabian sites, in modern-day United Arab Emirates (UAE). Of these, 24 individuals come from the Neolithic graveyard of al-Buhais 18 and shell midden Umm al-Quwain (Kutterer and Uerpmann 2017), 19

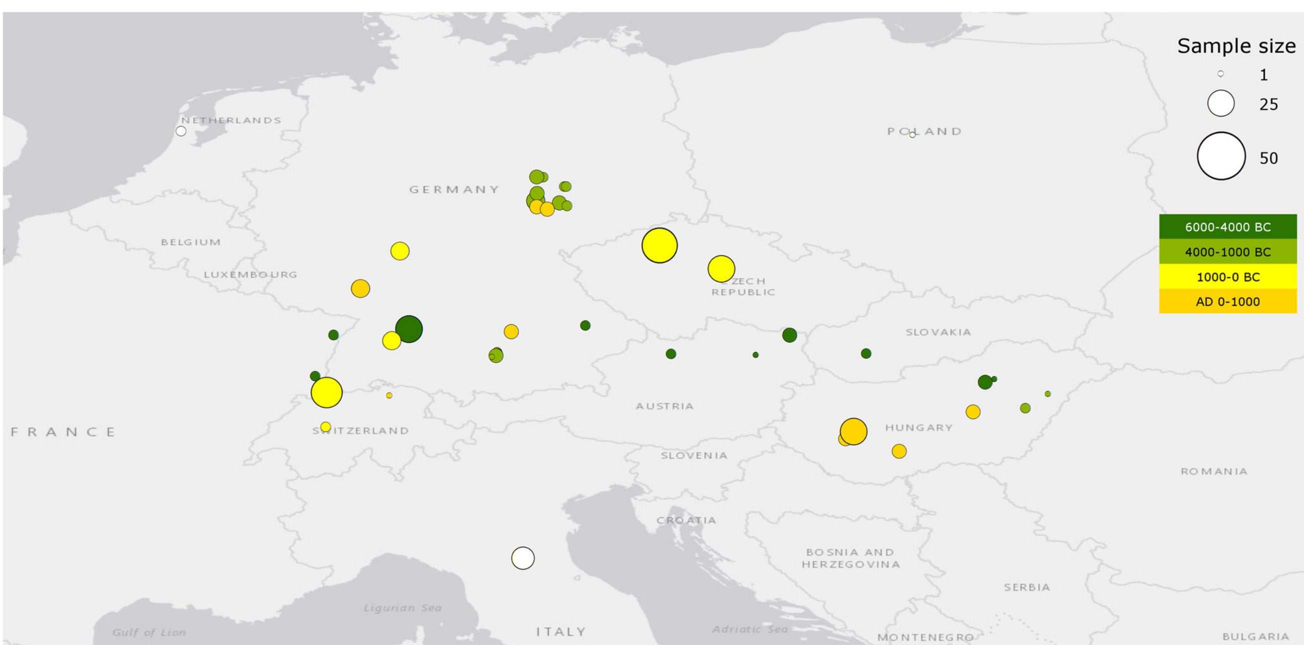

Fig. 2 Detailed map of all sites from Central Europe. Sites are categorized by periods

individuals come from seven Bronze Age tombs (Gregoricka 2014), and two skeletons were recovered at Jebel al-Emeilah, dating to Middle Sasanian period (Kutterer et al. 2015). Some sites are located on or near the coasts of the Persian and Oman Gulfs such as Umm al-Quwain, Umm an-Nar Island, Tell Abraq, Mowaihat, or Unar 1, while al-Buhais 18 and Jebel al-Emeilah are situated in the inland desert basin.

Seventy individuals from five sites represent the Peruvian region. Nine individuals derive from two Wari sites (AD 600–1000)—peripheral village Beringa in the Majes Valley of southern Peru (Knudson and Tung 2011) and secondary center Conchopata in the central Peruvian Andes (Tung and Knudson 2011). Fifty-four individuals belong to two sites in the Rimac Valley inhabited by Ychsma people—Armatambo and Rinconada Alta (Marsteller et al. 2017), while seven Chincha people are from the site of Pampa de los Gentiles (Knudson et al. 2016). Three latter sites are dated to the Late Intermediate Period (AD 900–1470).

The American Midwest studies represent a combination of two close regions—the Mississippi River floodplain of the American Bottom, and the Fort Ancient region around the mouths of the Great and Little Miami Rivers in Ohio. Researchers working in both regions have produced data from 201 individuals in total. More than half comes from the Cahokia site, located near the modern-day city of St. Louis, Missouri (Slater et al. 2014; Thompson et al. 2015), and the rest are from seven Fort Ancient sites (Cook and Price 2015). The majority of tooth pairs are Early–Late ($n = 183$). Only four individuals have data for teeth from all three childhood categories. The most individuals are dated from the 11th to 15th centuries AD.

Cobern Street (Kootker et al. 2016), and Victoria and Albert Marina Residence (Mbeki et al. 2017) are two eighteenth–nineteenth century burial grounds in Cape Town, South Africa. Since both are "informal" or pauper cemeteries, people buried there include slaves, sailors, soldiers, convicts, and exiles. Similar to the Cis-Baikal studies, first, second, and third molars of many individuals were analyzed enabling the study of multiple migrations during childhood.

The Central Europe category is here broadly defined, ranging from Alsace in the west to Hungary in the east, and from central Germany in the north to the Alps and Pannonian Plain in the south (Fig. 2). Forty-two sites can be divided into four main periods: Neolithic (6th–5th millennium BC); Eneolithic/Chalcolithic/Bronze Age (4th–2nd millennium BC); Iron Age (1st millennium BC); Roman/Migration/Early Medieval (1st millennium AD). Although we are aware that such categorization is far from perfect, for example, lengths of periods are different and sites from different periods do not exactly overlap each other geographically, we argue that it can at least illustrate some interesting similarities or differences.

Results and discussion

In the overall dataset, a majority of individuals (around 66% or 77% depending on the tooth pair) possess an offset between two paired teeth smaller than 0.0005 (Fig. A2). The number of individuals for whom the offset is lower than 0.001 varies from 77.5% (ΔL-M) to 87.0% (ΔL-E). The percentage for ΔM-E is 82.2% (Tables 1 and 2). The number of individuals with an offset between 0.001 and 0.002 varies from 7.1% to 13.7%, while individuals with $\Delta^{87}Sr/^{86}Sr$ between two teeth greater than 0.002 represent 5.9–8.8% of the sample.

As could be expected, the reported $\Delta^{87}Sr/^{86}Sr$ variability differs significantly between different regions and time periods (Figs. 3, 4, 5, and 6, Table 3). While individuals at some sites exhibit consistently low $\Delta^{87}Sr/^{86}Sr$ values, for example, in Southeastern Arabia (ΔL-E—minimum = − 0.00010; maximum = 0.00010; $\sigma = 0.00004$, $n = 34$), other individuals had very large differences between two teeth, for example, those buried in Cape Town (ΔL-E—minimum = − 0.01494; maximum = 0.00624; $\sigma = 0.00340$, $n = 37$).

There are also differences between tooth pairs across sites and regions, indicating that people moved during different periods of their childhood. For example, in Cis-Baikal Lokomotiv, large $\Delta^{87}Sr/^{86}Sr$ is common between early and middle teeth as well as between middle and late teeth (Fig. 3a). However, because the dietary change is frequent and directed to sources with both lower and higher strontium isotope ratios, the resulting difference between early and late teeth is reduced. By contrast, greater differences seem to be more frequent rather between early and middle childhood than between middle and late childhood at Late Neolithic Ust'-Ida. The highest overall variability in this region can be then seen in the Khuzhir-Nuge XIV individuals.

Both case studies of Cis-Baikal and Cape Town (Figs. 3a and 4a) demonstrate the importance of analyzing more than two teeth per individual. Many of these individuals exhibit a large offset between all three tooth pairs indicating multiple dietary/residential changes during childhood. Others exhibit small ΔE-L, but large ΔE-M and ΔL-M. If only early and late forming teeth are analyzed, as is the practice of most studies, the changes occurring among these individuals might not be observable at all.

In general, small $\Delta^{87}Sr/^{86}Sr$ values (≤ 0.0001) which can be observed, for example, in Southeastern Arabia (Fig. 3b),

Table 1 Percentage of different tooth pairs according to offset size

Tooth pair	n	≤ 0.001	0.001–0.002	0.002–0.003	≥ 0.003
ΔL-E	700	87.0%	7.1%	2.9%	3.0%
ΔM-E	340	82.1%	11.2%	3.8%	2.9%
ΔL-M	285	77.5%	13.7%	3.5%	5.3%

Table 2 Basic statistical description of different tooth pairs

Tooth pair	*n*	Minimum	Maximum	Mean	SD	Mean (AV)
ΔL-E	700	− 0.01494	0.00624	− 0.00009	0.00125	0.00052
ΔM-E	340	− 0.00478	0.01313	0.00006	0.00127	0.00059
ΔL-M	285	− 0.02273	0.00607	− 0.00024	0.00208	0.00085

may indicate either a lack of residential mobility between early childhood and late adolescence or that mobility did occur but was solely within or between isotopically similar areas. Although some researchers suggest that even a difference of 0.00005 between two teeth is “large enough to be considered as evidence of a change of the predominant living areas between childhood and adolescence” (Kutterer and Uerpmann 2017: 85), we suggest caution in this regard because such a small offset could also be caused only by slight dietary change independent of any movement (cf. Knudson et al. 2016).

High $\Delta^{87}Sr/^{86}Sr$ values among forager communities of the Cis-Baikal region are not surprising due to the character of these populations. As researchers (e.g., Haverkort et al. 2010), however, rightly note, due to the nature of hunting-gatherer subsistence strategies, it is difficult if not impossible to interpret these results purely in terms of residential mobility. First, the formation of each permanent molar’s enamel takes several years, so the measured $^{87}Sr/^{86}Sr$ values of bulk enamel samples are merely averages of the strontium intake during that time period and thus cannot provide information about short-term (i.e., annual or seasonal) movements (Montgomery

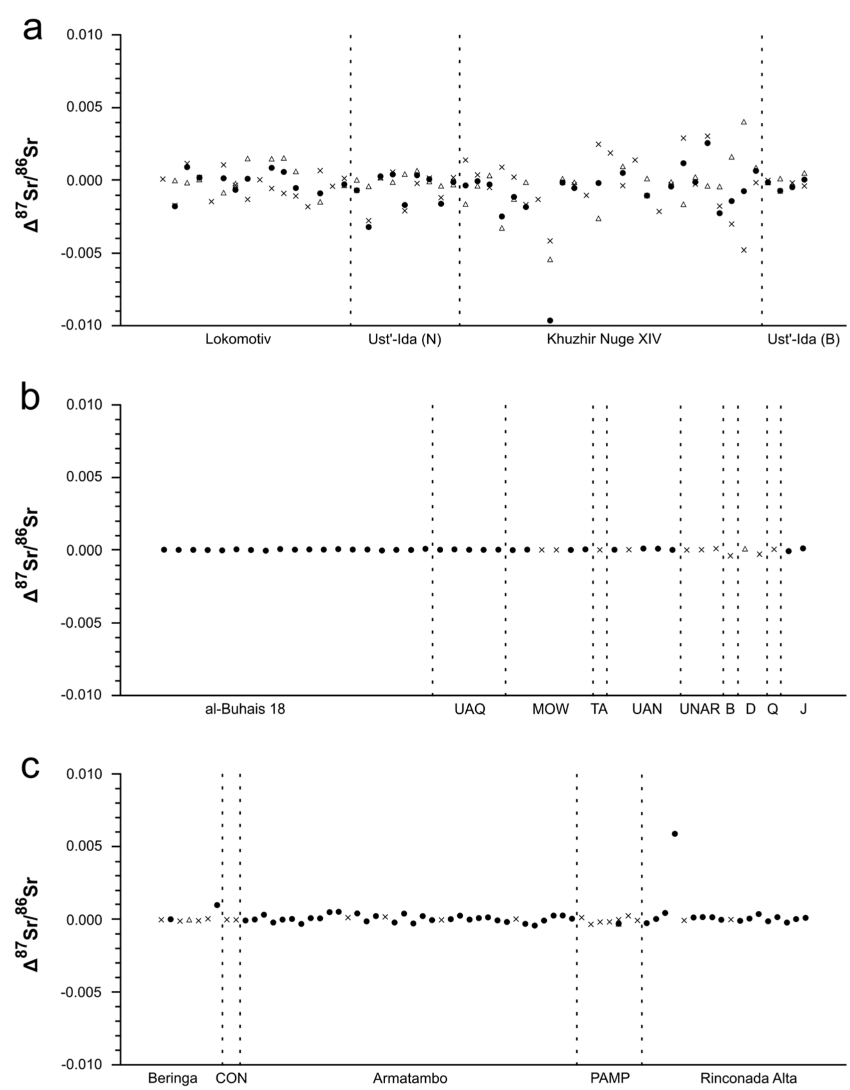

Fig. 3 Comparison of $\Delta^{87}Sr/^{86}Sr$ variability in different regions/periods. (**3a**) Cis-Baikal; (**3b**) Southeastern Arabia; (**3c**) Peru. Abbreviations: N = Late Neolithic; B = Bronze Age; UAQ = Umm al-Quwain 2; MOW = Mowaihat Tomb B; TA = Tell Abraq; UAN = Umm an-Nar Island; UNAR = Unar 1; B = Bidya 1; D = Dibba 76; Q = Qidfa 4; J = Jebel al-Emeilah; CON = Conchopata; PAMP = Pampa de los Gentiles. Symbols: full circle = ΔL-E; cross = ΔM-E; triangle = ΔL-M

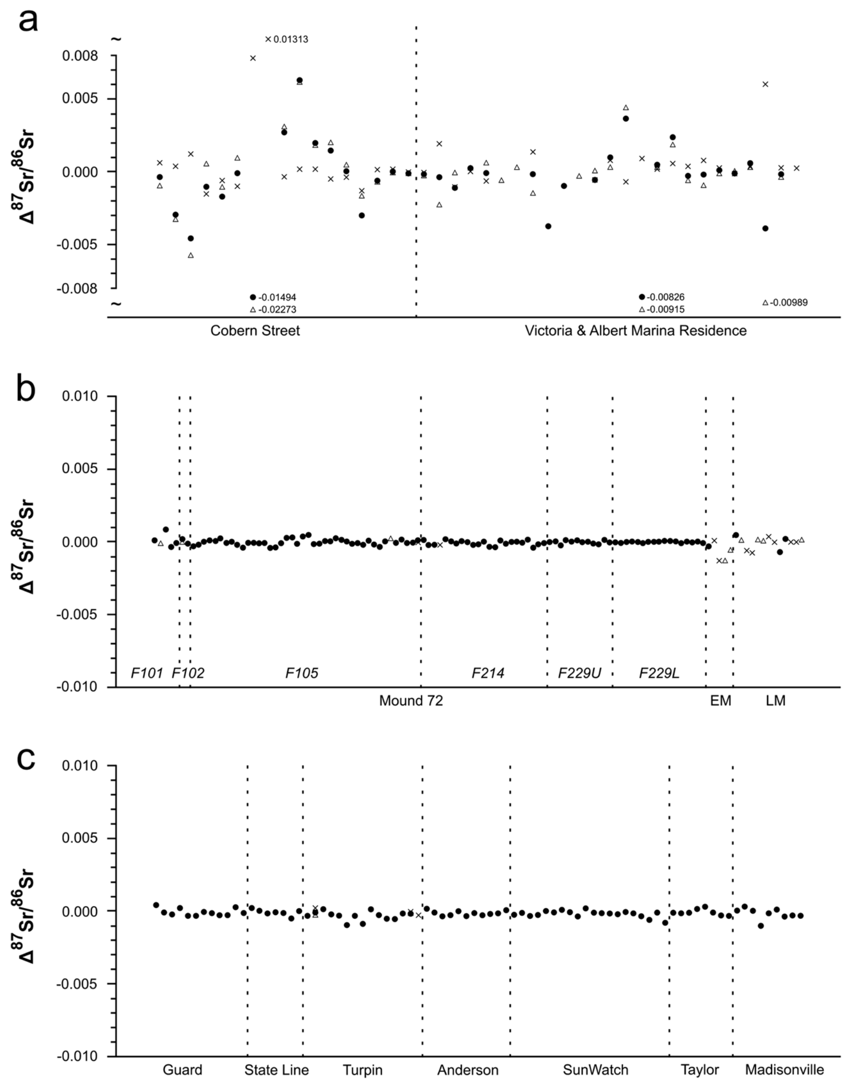

Fig. 4 Comparison of $\Delta^{87}Sr/^{86}Sr$ variability in different regions/periods. (**4a**) Cape Town; (**4b**) Cahokia; (**4c**) Fort Ancient. Abbreviations: EM = Another Early Mississippian; LM = Later Mississippian. Symbols: full circle = ΔL-E; cross = ΔM-E; triangle = ΔL-M

2010). Second, people likely did not move from one geochemical province to another in perfect periodicity. Their residence at different places could be of variable duration on each occasion, in addition to varying between individuals, and over time. Third, climate change could significantly influence the availability of specific faunal and floral sources, and since most sampled individuals come from different generations, they might consume different diets even within the same catchment area. Fourth, the size of the catchment area from which resources were obtained could also change over time and expand to geochemically distinct areas.

The results from the Cape Town burial populations are in accordance with the very high number of identified non-locals at these sites, with 54.5% at Cobern Street and 63% at Victoria and Albert Marina Residence, and with the main conclusion that migration was primarily related to long-distance forced migrations of enslaved individuals (Kootker et al. 2016; Mbeki et al. 2017). On the other hand, one needs to consider that the presumed local range is exceptionally wide, from 0.7086 to 0.7179, which can also partially explain unusually high $\Delta^{87}Sr/^{86}Sr$ values.

A third region with highly variable $\Delta^{87}Sr/^{86}Sr$ is Iron Age Central Europe (Fig. 6a). Several mechanisms have been proposed to explain this pattern. First, the observed differences could be caused by varying land use strategies in the geologically heterogeneous environments, in which many of these sites are situated (Scheeres et al. 2013, 2014). Compared to earlier periods, new technological improvements, such as iron plowshares, enabled exploitation of less fertile soils and gave people more flexibility in selecting farming land. "Cultivated land plots may have changed frequently, even within a few years (alternating Sr isotope ratios within the same jaw), or fluctuated gradually" (Scheeres et al. 2013: 3622). This explanation can be supported by comparison with two Iron Age sites in Italy (MB and MV on Fig. 6a), which are in more homogeneous geological settings and have less variable

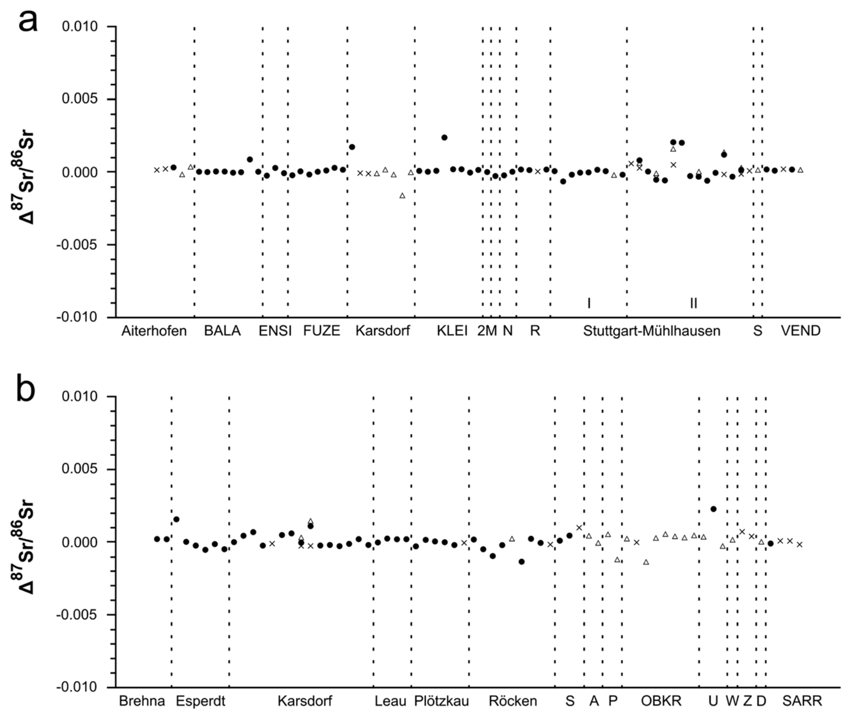

Fig. 5 Comparison of $\Delta^{87}Sr/^{86}Sr$ variability in different regions/periods. (**5a**) Neolithic CE; (**5b**) Eneolithic-Bronze Age CE. Abbreviations: BALA = Balatonszárszó; ENSI = Ensisheim-Les Octrois; FUZE = Füzesabony-Gubakút; KLEI = Kleinhadersdorf; 2 M = Mezőkövesd-Mocsolyás and Mitterndorf im Tullnerfeld; N = Nitra; R = Rutzing; S (**5a**) = Souffelweyersheim; VEND = Vendenheim; S (**5b**) = Serbitz; A = Augsburg-Hugo-Eckener-Straße; P = Haunstetten–Postillionstraße; OBKR = Königsbrunn–Obere Kreuzstraße; U = Haunstetten–Unterer Talweg; W = Wehringen–Hochfeld; Z = Zauschwitz; D = Debrecen–Dunahalom; SARR = Sarretudvari–Őrhalom. Symbols: full circle = ΔL-E; cross = ΔM-E; triangle = ΔL-M

$\Delta^{87}Sr/^{86}Sr$. The second option is that high $\Delta^{87}Sr/^{86}Sr$ in individuals reflects the residential change of larger groups that involved whole families, which would support the idea of historic "Celtic migrations" based on ancient written sources (Scheeres et al. 2014: 507). Third, mobility during childhood can be also explained in terms of fosterage, which could have lasted from infancy until marriage and whereby children might have been raised by one foster family or successive fosterers (Knipper et al. 2018; Scheeres et al. 2014). This possibility is documented in written sources and was supported by strontium analysis of children and juveniles (Müller-Scheeßel et al. 2015). Possible participation of juvenile boys in seasonal herding of cattle was also suggested for some sites, for example Münsingen-Rain (Scheeres 2014: 32–33), while for the Glauberg hillfort, researchers propose the hypothesis that high $\Delta^{87}Sr/^{86}Sr$ was caused by supplying food from

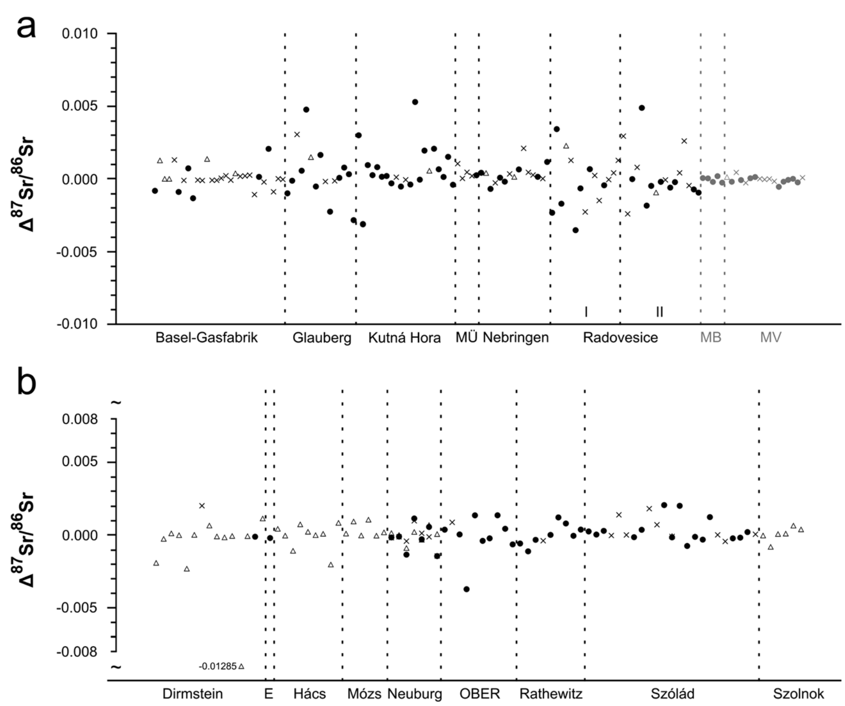

Fig. 6 Comparison of $\Delta^{87}Sr/^{86}Sr$ variability in different regions/periods. (**6a**) Iron Age CE; (**6a**) Roman-Early Medieval CE. Abbreviations: MÜ = Münsingen-Rain; MB = Monte Bibele; MV = Monterenzio Vecchio; E = Elsau; OBER = Obermöllern. Symbols: full circle = ΔL-E; cross = ΔM-E; triangle = ΔL-M

Table 3 Descriptive statistics for 10 case study regions/periods

Region (tooth pair)	*n*	Mean (AV)	SD	Region (tooth pair)	*n*	Mean (AV)	SD
Cis-Baikal	**54**			**Cape Town**	**42**		
ΔL-E	44	0.00101	0.00174	ΔL-E	37	0.00191	0.00340
ΔM-E	54	0.00111	0.00149	ΔM-E	37	0.00125	0.00271
ΔL-M	44	0.00086	0.00141	ΔL-M	38	0.00226	0.00463
SE Arabia	**45**			**Neolithic CE**	**77**		
ΔL-E	34	0.00003	0.00004	ΔL-E	59	0.00033	0.00060
ΔM-E	10	0.00009	0.00016	ΔM-E	15	0.00022	0.00028
ΔL-M	1	0.00003	–	ΔL-M	17	0.00042	0.00069
Peru	**70**			**E/BA CE**	**68**		
ΔL-E	51	0.00031	0.00085	ΔL-E	42	0.00038	0.00060
ΔM-E	19	0.00009	0.00013	ΔM-E	12	0.00028	0.00040
ΔL-M	2	0.00017	0.00015	ΔL-M	18	0.00045	0.00063
Cahokia	**119**			**Iron Age CE**	**116**		
ΔL-E	102	0.00014	0.00020	ΔL-E	59	0.00116	0.00172
ΔM-E	11	0.00033	0.00049	ΔM-E	46	0.00066	0.00106
ΔL-M	10	0.00028	0.00047	ΔL-M	11	0.00078	0.00090
Fort Ancient	**82**			**R/M/EM CE**	**86**		
ΔL-E	81	0.00024	0.00026	ΔL-E	41	0.00065	0.00099
ΔM-E	3	0.00018	0.00025	ΔM-E	19	0.00059	0.00085
ΔL-M	2	0.00022	0.00014	ΔL-M	42	0.00076	0.00210

N = number of individuals (for region/period; in bold) and number of tooth pairs. Mean (AV) = mean from $\Delta^{87}Sr/^{86}Sr$ absolute value

different settlements, representing the economic hinterland of this "princely seat" (Knipper et al. 2014). Other explanations include settlement centralization, or children representing hostages or slaves (Knipper et al. 2018). It should be emphasized that all of these different types of mobility might have existed simultaneously and that strontium isotope analysis alone cannot distinguish between them.

The rest of the sites in the compiled data set exhibit $\Delta^{87}Sr/^{86}Sr$ variability that is intermediate between the aforementioned examples. In many such cases, childhood mobility has been inferred based on the observed $\Delta^{87}Sr/^{86}Sr$ values, but the exact number of mobile individuals cannot be accurately estimated without more detailed studies of the local (and regional) geological, environmental, and archeological contexts. Detailed discussions of the case-specific contexts and interpretations of all of the strontium isotope studies cited herein are nevertheless beyond the scope of this review and we refer the reader to the original papers.

Possible outcomes and explanations of multiple tooth analysis

Analyzing multiple teeth per individual can provide new insights into childhood mobility; nevertheless, the range of possible explanations is wide and varied. For this summary, we assumed that the local isotope range is defined correctly, and we excluded the possibility of post-mortem mobility (e.g., Keegan 2009). For simplicity, we consider analysis of only two teeth (early and late). We also highlight the well-known fact that $^{87}Sr/^{86}Sr$ analysis cannot distinguish mobility between two locations with similar bioavailable $^{87}Sr/^{86}Sr$. Therefore, all $^{87}Sr/^{86}Sr$ analyses potentially underestimate the real numbers of nonlocal individuals and consequently the true amount of mobility. This can be solved only through incorporation of other evidence, whether they are additional isotopic analyses (e.g., oxygen or lead) or complementary archeological or historical data.

We summarize potential outcomes and interpretations involved in multiple tooth $^{87}Sr/^{86}Sr$ analysis in Fig. 7 and Table 4. The complexity and variability in the results obtained from strontium isotope analyses using the multiple tooth sampling approach are illustrated via several hypothetical outcomes. Outcomes 1A and 1B, in which both teeth have local signals and their explanation thus looks straightforward, do not prove that individual did not move during their life. They only suggest that he/she did not move between regions with different bioavailable $^{87}Sr/^{86}Sr$ ranges. Especially in case of 1B, where the $\Delta^{87}Sr/^{86}Sr$ between early and late teeth is greater than the defined offset for the site (e.g., 0.001), possible childhood mobility cannot be excluded, although the change in dietary sources is equally probable.

Other outcomes indicate dietary or residential change more directly. Outcomes 2A and 3A refer to the cases when one of the teeth has a local $^{87}Sr/^{86}Sr$ signal and the second one a non-

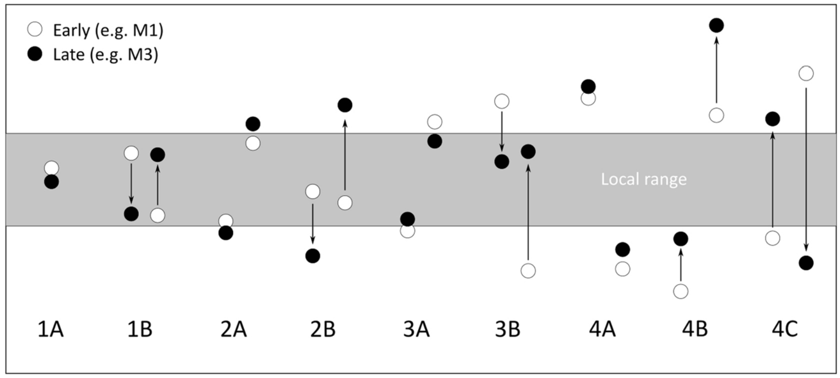

Fig. 7 Potential outcomes of strontium isotope analysis of two teeth from the same individual

Table 4 Potential outcomes and explanations involved in strontium isotope analysis of two teeth from same individual

Local/non-local		$\Delta^{87}Sr/^{86}Sr$	Possible explanations
1A:	Both teeth local	< OFFSET	– Locally born, no residential change, no change in dietary sources
			– (Non-)locally born, mobility between regions with identical $^{87}Sr/^{86}Sr$ ratios
1B:		> OFFSET	– Locally born, no residential change, but change in dietary sources (e.g., varying land-use strategies)
			– (Non-)locally born, mobility between regions with similar, although not identical, $^{87}Sr/^{86}Sr$ ratios
2A:	ET local, LT non-local	< OFFSET	– Locally born, no residential change, but change in dietary sources (consumption of imported non-local food)
			– Locally born, mobility during childhood (e.g., residential change, fosterage, herding)
			– Non-locally born, residential change during adulthood from region with similar $^{87}Sr/^{86}Sr$ ratios (but for which both ET and LT are local)
2B:		> OFFSET	– Locally born, no residential change, but change in dietary sources (consumption of imported non-local food)
			– Locally born, mobility during childhood (e.g., residential change, fosterage, herding)
			– Non-locally born (in region with identical $^{87}Sr/^{86}Sr$ ratios), multiple residential changes/changes in dietary sources (at least one during childhood and one during adulthood)
3A:	ET non-local, LT local	< OFFSET	– Non-locally born, residential change during childhood
			– Non-locally born, residential change during adulthood from region with similar $^{87}Sr/^{86}Sr$ ratios (but for which both ET and LT are local)
			– Locally born to mother consuming non-local food
3B:		> OFFSET	– Non-locally born, residential change during childhood
			– Non-locally born, change in dietary sources during childhood and residential change during adulthood
			– Locally born to mother consuming non-local food
4A:	Both teeth non-local	< OFFSET	– Non-locally born, no residential change or change in dietary sources during childhood, but immigration to the site during adulthood
			– Non-locally born, mobility between regions with identical $^{87}Sr/^{86}Sr$ ratios during childhood, and immigration to the site during adulthood
			– Locally born to mother consuming non-local food, and consuming non-local food during his/her entire childhood (with or without mobility)
4B, 4-C:		> OFFSET	– Non-locally born, residential change during adulthood and residential change/change in dietary sources during childhood
			– Non-locally born, residential change during childhood, but consuming non-local food during the time of LT formation
			– Non-locally born, residential change during childhood, which appeared exactly during the time of LT formation[a]
			– Locally born to mother consuming non-local food, and consuming non-local food (different from that consuming by his/her mother) during his/her entire childhood (with or without mobility)

ET = Early tooth (e.g., M1); LT = Late tooth (e.g., M3); OFFSET = $\Delta^{87}Sr/^{86}Sr$ between two teeth which is not likely produced only by small change in eating habits (e.g., 0.001)

[a] Therefore, Sr ratio in LT is a combination of local and non-local signatures (it is possible only when LT Sr ratio is between ET Sr ratio and local range; i.e., first 4B example in Fig. 7)

local ^{87}Sr/^{86}Sr ratio. In outcome 2A, the "local" tooth is an early one, indicating an individual's local origin and dietary/residential change during late childhood. The person might consume imported non-local food, move away temporarily, or start a more mobile lifestyle. The reverse situation is represented by outcome 3A that indicates a non-local origin and migration to the site during childhood. However, both outcomes might be also explained in terms of migration during adulthood from a region with similar ^{87}Sr/^{86}Sr ratios. Although these outcomes seem to be clear evidence for dietary/residential change, in practice it should be interpreted with caution because the boundary between local/non-local signatures is often not very clear. Outcomes 2B and 3B are clearer in this sense because the Δ^{87}Sr/^{86}Sr between teeth is greater than the offset defined for the site.

Outcome 4A (both teeth with non-local signals and relatively small Δ^{87}Sr/^{86}Sr) suggests dietary/residential change after adolescence. Although additional mobility during childhood cannot be excluded, outcomes 4B and 4C provide better evidence for multiple mobility events during an individual's lifetime. However, since individuals in these cases are probably non-local, it is impossible to estimate the precise Δ^{87}Sr/^{86}Sr offset value typical for their home location.

Adding the third tooth (e.g., M2 for middle childhood) into the analysis can further specify the age at which dietary/residential change occurred. On the other hand, the range of possible explanations becomes even wider. Regarding the possibility of distinguishing between change in dietary sources and residential mobility, strontium isotope analysis does not provide a simple answer. Other multiple tooth isotopic analyses (δ^{18}O, δ^{15}N, and δ^{13}C) or other archeological methods need to supplement this method.

Possible interpretations of childhood mobility

There is no simple interpretation for any of the multiple tooth analysis outcomes (Fig. 7). Anthropological and historical literature provides many examples of different types of childhood mobility, which can result in the same or similar Sr isotope outcomes in human teeth. For this reason, it is necessary to complement Sr isotope results with other lines of evidence. Some of the main types of childhood mobility are discussed below; although this list should not be considered exhaustive, it is intended to illustrate the diversity of this phenomena.

Residential change of whole kin group

Probably the most common movement of children was together with their kin group, whether as migration of a single family or a larger community group. The potential reasons for residential change include many factors, for example, economic, demographic, social, ideological, ecological, or political. Nevertheless, it is worth noting that migration patterns often comprise a two-way flow of people including migration and return migration (Anthony 1990: 904), and thus it is possible that some of these children returned to their region of birth later in life, while other children might be born in the new environment and moved with their returning parents (Hadley and Hemer 2011: 75).

Fosterage

Fosterage, sometimes called "children circulation" (Leinaweaver 2008), is a practice characteristic of many societies, e.g., medieval Ireland or modern-day Peru, when a child does not reside with his/her own parents. Distinct from adoption, the child's natural parents remain the acknowledged parents. Scholars distinguish several types of fosterage. A main distinction is made between crisis fosterage, by close family kin, and allegiance fosterage. The latter can be further divided between patronal allegiance fosterage (child-raising by status superior) and cliental allegiance fosterage (raising by status inferior) (Parkes 2006: 359). Fosterage can be for free, so-called fosterage for love, usually undertaken by close kin or family friends, or parents may pay a fosterage fee, which depended on the child's sex and parents' status (Hemer 2014: 137). The main functions of this practice are the formation of alliances between households and/or the provision of education (Hemer 2014: 138). Fosterage could have lasted from infancy until marriage and children might be fostered by a several successive fosterers (Parkes 2006: 362). This would divide financial burden associated with rearing a child between multiple families, and at the same time extend the allegiance network (Hemer 2014: 138). Sometimes, children are also fostered if poor families have difficulties providing sufficient sustenance for them. A wealthier fostering family may provide children with basic needs, while receiving extra labor in return (Lancy 2018: 200; Sieff 1997: 523). Besides fosterage, children might have been raised by institutions, for example, a monastery or boarding school. Another example of fosterage is in cases when children primarily receive specialized training from a master in a craft, art, or medicine, such as apprenticeship (Lancy 2012).

Herding

Many studies of the role of children in different societies showed that they are often involved in the tasks of keeping livestock even from a very young age (Knipper 2009: 294–297). In Peru, for instance, children participate in herding chores since they are barely able to walk and may be entrusted with a small herd alone by the age of 5 or 6 years (Bolton et al. 1976: 467). Similarly, African Fulani boys are actively involved in cattle herding activities with their older brothers or father from the age of six, but sometimes even earlier (Denga 1983: 171; Lott and Hart 1977: 181). In terms of gender, men and boys are usually responsible for herding livestock (Lancy 2018: 92; Whiting and Edwards 1988: 63–66); however, there are examples of both girls and boys being involved in herding activities. For example, children of both sexes take care of llamas and alpacas in the Andes (Bolton et al. 1976: 467), and among Tanzanian Datoga, there are about the same number of female and male herders. Small livestock and calves are almost equally guarded by girls and boys, while there are slightly more males among cattle herders (Sieff 1997: 536–537). Kel Ewey Tuareg children of both sexes also work from early age. At about the age of 7, they help their older siblings to watch over the goats while they are grazing. At about 10 years old, girls start to herd goats on their own, whereas boys travel with their fathers and camel caravans for several months on distances up to 900 km (Spittler 2012: 59–61). Overall, in most pastoralist societies children spent many hours away from the settlement in herding activities (Lancy 2018: 117–118).

Forced mobility

Children and women have often been overrepresented among captives in many societies (Cameron 2016), and since warfare, raiding, and kidnapping were common in many times and places, unwilling (and usually violent) or forced migration of children is also a possible interpretation in many contexts. Some captured children might be adopted or married into families, while some become slaves. Others were kept as hostages or occupy some marginal positions such as household servants. Children did not have to be captured to end up in slavery. They could be also sold by their poor parents in return for food in times of starvation or they were born as slaves (Patterson 1982). Once a child became “property”, he/she could be traded, and moved, from one master to another. Interestingly, some children were also part of the other side of the coin. For example, written, as well as archeological, evidence shows that children clearly accompanied Viking armies during raids (Hadley and Hemer 2011: 65). And it is possible that some individuals age 10 or even younger might be directly involved in combat (Kamp 2001: 26).

Child marriage and post-marital residence

Although the marriage age is often set at 18 in the majority of modern countries, it is not rare when people, especially girls, got married much younger. The United Nations Population Fund estimates that 12% of girls around the world become brides before the age of 15 (Loaiza and Wong 2012). Among some schools of Islamic legal thought, for example, the range of minimum marriageable ages for males is between 15 and 18, while for females this extends from a high of 17 down to as young as 9 (Büchler and Schlatter 2013). Similarly, in Ancient Rome, the legal minimum age of marriage for girls was 12 and for boys 14, but there is also evidence for children married at 6 and 7 (Hopkins 1965). In early medieval Germanic societies, people also usually married very young, girls aged 12 to 14 and boys between 14 and 16 (Wemple 1993: 229). Therefore, in some rare cases, multiple-tooth analysis can potentially reveal post-marital mobility occurring at a young age since third molars develop relatively slowly and the process of crown mineralization is not completed until approximately 14 years of age (AlQahtani et al. 2010).

Temporary matrilocal residence was common among some societies. For example, young indigenous couples living on Aleutian Islands in the Northern Pacific Ocean remained with the wife’s parents after their marriage and moved to the husband’s family home only after the first child was born (Lantis 1984: 176). Similarly, men from the North American tribe Havasupai usually lived in their wife’s parents’ camp until she had borne one or two children. Afterward, the couple might establish their new home near either his or her parents’ camp (Spier 1928: 222). Post-marital residence was initially matrilocal also among the South American Tupinamba, but the husband’s goal was to free himself and his wife from dependence on the in-laws and move to his own parents’ longhouse (Métraux 1948: 111–112). In such cases, the residential mobility of newly born or very young children can be revealed through differences in strontium ratios between the early forming teeth (e.g., deciduous teeth which start to mineralize in utero) and later forming ones.

Conclusion

Although the analyzed dataset has clear spatial and temporal biases and is lacking in representativeness, this study has revealed several important findings. The reported $\Delta^{87}Sr/^{86}Sr$ variability differs significantly between different regions and time periods. This cannot be explained only by different patterns of subsistence or by diverse geological conditions around each site, and thus must reflect to some extent different patterns of childhood mobility in the past. Previous applications of the multiple tooth sampling approach for strontium isotope studies of human paleomobility have clearly demonstrated that childhood mobility was more common than previously recognized. The increasing number of studies utilizing this approach in recent years perhaps illustrates a renewed interest in social (e.g., age-related) variation in patterns of human migration and mobility, as well as methodological advances permitting higher resolution reconstruction of past lifeways and life histories. Nonetheless, the various potentials, limitations, and complicating variables of the multi-tooth sampling approach merit more explicit consideration.

First, a minimal $\Delta^{87}Sr/^{86}Sr$ cutoff of 0.001 to detect residential change during childhood/adolescence has been proposed and applied in several recent studies. This proposed cutoff (0.001) is approximately two orders of magnitude larger than the typical measurement error (0.00001) of strontium isotope analysis (2SE) and thus is extremely unlikely to be the result of analytical error or random variation. However, as the degree of normal variation in $^{87}Sr/^{86}Sr$ within a single (non-mobile) individual is not well characterized, caution is merited in the use of such an absolute cutoff value for distinguishing between local and non-local individuals. Future research should focus on more precise estimation of the expected range of $^{87}Sr/^{86}Sr$ variation between different tissues within a single individual (e.g., intra-individual variation). The approach proposed by Knipper et al. (2018) should be expanded to larger datasets including individuals that are documented to have been stationary (non-mobile) and to a greater diversity of biogeochemical and geographical settings.

Multiple tooth $^{87}Sr/^{86}Sr$ analysis, as well as isotopic provenancing in general, has its limitations. The extent of identified childhood mobility will generally remain an under-estimation since it is usually impossible to reveal mobility between two places with similar bioavailable $^{87}Sr/^{86}Sr$ signatures. This limitation is, however, not specific to the multiple tooth sampling approach, but is inherent to (single) isotope approaches more generally. Therefore, it is beneficial to supplement this method, when possible, with other isotopic proxies, for example, multiple tooth $\delta^{18}O$, $\delta^{15}N$, and $\delta^{13}C$ analyses or other archeological methods. Of course, childhood mobility can be also revealed by analyzing isotope ratios in the remains of children themselves (i.e., of individuals who died during childhood, as opposed to tissue samples from adults which form during childhood). Such an approach permits the identification of child migrants that did not survive to adulthood (Hadley and Hemer 2011: 72). Conversely, isotope analysis of certain deciduous teeth that form solely or primarily in utero could in principle be used to investigate the mobility/migration patterns of mothers during pregnancy.

As nuanced interpretations cannot be deduced from multiple tooth $^{87}Sr/^{86}Sr$ analysis alone, because every outcome can be explained in several different ways, the results should always be placed within an appropriate archeological, historical, and ethnographic context. In order to reveal dietary/residential changes at finer temporal resolutions, it is preferable to analyze teeth from three age categories (e.g., M1, M2, and M3). The incorporation of four or more permanent teeth does not provide much additional information in this respect since the formation ages of many teeth overlap. By contrast, the multiple tooth sampling approach involves significantly higher investments in time and costs than the traditional single tooth sampling approach, and it also destroys a larger amount of archeological material since the strontium isotope analysis is a destructive method, as is the case with most types of biochemical analysis of human remains. As such, decisions about which sampling approach to employ will likely be influenced by these practical considerations, as well as the specific contexts of the individual case studies. Therefore, analysis of multiple tooth should be conducted only in cases where there is a justified assumption that the results will provide new and meaningful findings.

Acknowledgments This manuscript was prepared during V.H.'s internship at Leiden University, which has been funded by the Erasmus+ Traineeship grant. J.E.L. is supported in part by the ERC-Synergy project NEXUS1492 which has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement no. 319209. The research described in this paper was accomplished with support from the project "Lifestyle as an unintentional identity in the Neolithic" (Project 19-16304S), financed by the Czech Science Foundation. The authors gratefully acknowledge the insightful critiques and comments of two anonymous reviewers.

References

AlQahtani SJ, Hector MP, Liversidge HM (2010) Brief communication: the London atlas of human tooth development and eruption. Am J Phys Anthropol 142:481–490

Ammerman AJ, Cavalli-Sforza LL (1984) The Neolithic transition and the genetics of populations in Europe. Princeton University Press, Princeton

Anthony DW (1990) Migration in archeology: the baby and the bathwater. Am Anthropol 92(4):895–914

Bentley RA (2006) Strontium isotopes from the earth to the archaeological skeleton: a review. J Archaeol Method Theory 13:135–187

Bolton C, Bolton R, Gross L, Koel A, Michelson C, Munroe RL, Munroe RH (1976) Pastoralism and personality: an Andean replication. Ethos 4:463–481

Brown TA, Brown K (2011) Biomolecular archaeology: an introduction. Wiley-Blackwell, Chichester, West Sussex; Malden, MA

Büchler A, Schlatter C (2013) Marriage age in Islamic and contemporary Muslim family laws. A comparative survey. Electron J Islamic Middle Eastern Law 1:37–74

Buikstra JE, Price TD, Wright LE, Burton JA (2004) Tombs from the Copan acropolis: a life-history approach. In: Bell EE, Canuto MA, Sharer RJ (eds) Understanding early classic Copan. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia, pp 191–214

Burmeister S (2000) Archaeology and migration: approaches to an archaeological proof of migration. Curr Anthropol 14(4):539–567

Burmeister S (2016) Archaeological research on migration as a multidisciplinary challenge. Medieval worlds. Comp Interdisciplinary Stud 4:42–64

Cameron CM (2016) Captives: how stolen people changed the world. University of Nebraska Press, Lincoln & London

Cook RA, Price TD (2015) Maize, mounds, and the movement of people: isotope analysis of a Mississippian/Fort ancient region. J Archaeol Sci 61:112–128

Copeland SR, Sponheimer M, le Roux PJ, Grimes V, Lee-Thorp JA, de Ruiter DJ, Richards MP (2008) Strontium isotope ratios (87Sr/86Sr) of tooth enamel: a comparison of solution and laser ablation multicollector inductively coupled plasma mass spectrometry methods. Rapid Commun Mass Spectrom 22:3187–3194

Crawford S, Hadley DM, Shepherd G (2018) The Oxford handbook of the archaeology of childhood. Oxford University Press, Oxford

Denga DI (1983) The effect of mobile group counseling on nomadic Fulani's attitudes toward formal education. J Negro Educ 52:170–175

Eriksson G (2013) Stable isotope analysis of humans. In: Tarlow S, Stutz LN (eds) The Oxford handbook of the archaeology of death and burial. Oxford University Press, Oxford, pp 123–146

Eriksson G, Frei KM, Howcroft R, Gummesson S, Molin F, Lidén K, Frei R, Hallgren F (2018) Diet and mobility among Mesolithic hunter-gatherers in Motala (Sweden)—the isotope perspective. J Archaeol Sci Rep 17:904–918

Evans JA, Chenery CA, Fitzpatrick AP (2006) Bronze age childhood migration of individuals near Stonehenge, revealed by strontium and oxygen isotope tooth enamel analysis. Archaeometry 48:309–321

Evans JA, Montgomery J, Wildman G, Boulton N (2010) Spatial variations in biosphere 87Sr/86Sr in Britain. J Geol Soc 167:1–4

Faure G, Mensing TM (2005) Isotopes: principles and applications, 3rd. edn. Wiley & Sons, Inc, Hoboken, New Jersey

Fraser M, Sjödin P, Sanchez-Quinto F, Evans J, Svedjemo G, Knutsson K, Götherström A, Jakobsson M, Storå J (2018) The stone cist conundrum: a multidisciplinary approach to investigate Late Neolithic/Early Bronze Age population demography on the island of Gotland. J Archaeol Sci Rep 20:324–337

Frei KM, Mannering U, Kristiansen K, Allentoft ME, Wilson AS, Skals I, Tridico S, Louise Nosch M, Willerslev E, Clarke L, Frei R (2015a) Tracing the dynamic life story of a Bronze Age female. Sci Rep 5: 10431

Frei KM, Mannering U, Price TD, Iversen RB (2015b) Strontium isotope investigations of the Haraldskær woman—a complex record of various tissues. ArcheoSciences (39):93–101

Frei KM, Villa C, Jørkov ML, Allentoft ME, Kaul F, Ethelberg P, Reiter SS, Wilson AS, Taube M, Olsen J, Lynnerup N, Willerslev E, Kristiansen K, Frei R (2017) A matter of months: high precision migration chronology of a bronze age female. PLoS One 12: e0178834

Gregoricka LA (2014) Assessing life history from commingled assemblages: the biogeochemistry of inter-tooth variability in Bronze Age Arabia. J Archaeol Sci 47:10–21

Grimstead DN, Nugent S, Whipple J (2017) Why a standardization of strontium isotope baseline environmental data is needed and recommendations for methodology. Adv Archaeol Pract 5(2):184–195

Grupe G, Price TD, Schröter P, Söllner F, Johnson CM, Beard BL (1997) Mobility of Bell beaker people revealed by strontium isotope ratios of tooth and bone: a study of southern Bavarian skeletal remains. Appl Geochem 12:517–525

Hadley DM, Hemer KA (2011) Microcosms of migration: children and early medieval population movement. Childhood in the Past 4:63–78

Hadley DM, Hemer KA (2014) Medieval childhood: archaeological approaches. Oxbow Books, Oxford

Hakenbeck SE (2008) Migration in archaeology: are we nearly there yet? Archaeol Rev Cambridge 23:9–26

Haverkort CM, Weber A, Katzenberg MA, Goriunova OI, Simonetti A, Creaser RA (2008) Hunter-gatherer mobility strategies and resource use based on strontium isotope (87Sr/86Sr) analysis: a case study from Middle Holocene Lake Baikal, Siberia. J Archaeol Sci 35: 1265–1280

Haverkort CM, Bazaliiskii VI, Savel'ev NA (2010) Identifying hunter-gatherer mobility patterns using strontium isotopes. In: Weber A, Katzenberg MA, Schurr TG (eds) Prehistoric hunter-gatherers of the Baikal region, Siberia: bioarchaeological studies of past life ways. University of Pennsylvania Press, Philadelphia, pp 217–242

Hedman KM, Curry BB, Johnson TM, Fullagar PD, Emerson TE (2009) Variation in strontium isotope ratios of archaeological fauna in the Midwestern United States: a preliminary study. J Archaeol Sci 36: 64–73

Hedman KM, Slater PA, Fort MA, Emerson TE, Lambert JM (2018) Expanding the strontium isoscape for the American midcontinent: identifying potential places of origin for Cahokian and pre-Columbian migrants. J Archaeol Sci Rep 22:202–213

Hemer KA (2014) Are we nearly there yet? Children and migration in early medieval western Britain. In: Hadley DM, Hemer KA (eds) Medieval childhood: archaeological approaches. Oxbow, Oxford, pp 131–144

Hillson S (1996) Dental anthropology. Cambridge University Press, Cambridge, UK

Hodell DA, Quinn RL, Brenner M, Kamenov G (2004) Spatial variation of strontium isotopes (87Sr/86Sr) in the Maya region: a tool for tracking ancient human migration. J Archaeol Sci 31:585–601

Hoogewerff J, Papesch W, Kralik M, Berner M, Vroon P, Miesbauer H, Gaber O, Künzel KH, Kleinjans J (2001) The last domicile of the iceman from Hauslabjoch: a geochemical approach using Sr, C and O isotopes and trace element signatures. J Archaeol Sci 28:983–989

Hopkins MK (1965) The age of Roman girls at marriage. Popul Stud 18: 309–327

Hoppe KA, Koch PL, Furutani TT (2003) Assessing the preservation of biogenic strontium in fossil bones and tooth enamel. Int J Osteoarchaeol 13:20–28

Kamp KA (2001) Where have all the children gone?: the archaeology of childhood. J Archaeol Method Theory 8:1–34

Keegan WF (2009) Central plaza burials in Saladoid Puerto Rico: an alternative perspective. Lat Am Antiq 20(2):375–385

Knipper C (2009) Die räumliche Organisation der linearbandkeramischen Rinderhaltung: naturwissenschaftliche und archäologische Untersuchungen. Dissertation, Eberhard-Karls-Universität Tübingen

Knipper C, Meyer C, Jacobi F, Roth C, Fecher M, Stephan E, Schatz K, Hansen L, Posluschny A, Höppner B, Maus M, Pare CFE, Alt KW (2014) Social differentiation and land use at an early Iron age "princely seat": bioarchaeological investigations at the Glauberg (Germany). J Archaeol Sci 41:818–835

Knipper C, Pichler SL, Brönnimann D, Rissanen H, Rosner M, Spichtig N, Stopp B, Rentzel P, Röder B, Schibler J, Lassau G, Alt KW (2018) A knot in a network: residential mobility at the Late Iron Age proto-urban centre of Basel-Gasfabrik (Switzerland) revealed by isotope analyses. J Archaeol Sci Rep 17:735–753

Knudson KJ, Tung TA (2011) Investigating regional mobility in the southern hinterland of the Wari empire: biogeochemistry at the site of Beringa, Peru. Am J Phys Anthropol 145:299–310

Knudson KJ, Stanish C, Lozada Cerna MC, Faull KF, Tantaleán H (2016) Intra-individual variability and strontium isotope measurements: a methodological study using 87Sr/86Sr data from Pampa de los Gentiles, Chincha Valley, Peru. J Archaeol Sci Rep 5:590–597

Kootker LM, Mbeki L, Morris AG, Kars H, Davies GR (2016) Dynamics of Indian Ocean slavery revealed through isotopic data from the colonial era Cobern street burial site, Cape Town, South Africa (1750–1827). PLoS One 11:e0157750

Kristiansen K (2014) Towards a new paradigm? The third science revolution and its possible consequences in archaeology. Curr Swed Archaeol 22:11–34

Kutterer A, Uerpmann HP (2017) Neolithic nomadism in south-east Arabia—strontium and oxygen isotope ratios in human tooth enamel from Al-Buhais 18 and Umm al-Quwain 2 in the Emirates of Sharjah and Umm al-Quwain (UAE). Arab Archaeol Epigr 28:75–89

Kutterer A, Jasim SA, Yousif E (2015) Buried far from home: Sasanian graves at Jebel al-Emeilah (Sharjah, UAE). Arab Archaeol Epigr 26: 43–54

Laffoon JE (2012) Patterns of paleomobility in the ancient Antilles: an isotopic approach. Dissertation, Leiden University

Laffoon JE, Sonnemann TF, Shafie T, Hofman CL, Brandes U, Davies GR (2017) Investigating human geographic origins using dualisotope (87Sr/86Sr, δ18O) assignment approaches. PLoS One 12: e0172562

Lancy DF (2012) "First you must master pain": the nature and purpose of apprenticeship. Anthropol Work Rev 33:113–126

Lancy DF (2018) Anthropological perspectives on children as helpers, workers, artisans, and laborers. Palgrave Macmillan, New York

Lantis M (1984) Aleut. In: Damas D (ed) Handbook of North American Indians. Vol. 5, Arctic. Smithsonian Institution, Washington D.C., pp. 161–184

Leinaweaver JB (2008) Improving oneself: young people getting ahead in the Peruvian Andes. Lat Am Perspect 35:60–78

Lewis J, Coath CD, Pike AWG (2014) An improved protocol for 87Sr/86Sr by laser ablation multi-collector inductively coupled plasma mass spectrometry using oxide reduction and a customised plasma interface. Chem Geol 390:173–181

Loaiza E, Wong S (2012) Marrying too young: end child marriage. United Nations Population Fund, New York

Lott DF, Hart BL (1977) Aggressive domination of cattle by Fulani herdsmen and its relation to aggression in Fulani culture and personality. Ethos 5:174–186

Marsteller SJ, Knudson KJ, Gordon G, Anbar A (2017) Biogeochemical reconstructions of life histories as a method to assess regional interactions: stable oxygen and radiogenic strontium isotopes and late intermediate period mobility on the central Peruvian coast. J Archaeol Sci Rep 13:535–546

Mbeki L, Kootker LM, Kars H, Davies GR (2017) Sickly slaves, soldiers and sailors. Contextualising the Cape's 18th–19th century Green Point burials through isotope investigation. J Archaeol Sci Rep 11:480–490

Métraux A (1948) The Tupinamba. In: Steward JH (ed.) Handbook of South American Indians. Vol. 3, The Tropical Forest Tribes. Smithsonian Institution, Washington D.C., pp. 95–133

Montgomery J (2010) Passports from the past: investigating human dispersals using strontium isotope analysis of tooth enamel. Ann Hum Biol 37:325–346

Montgomery J, Evans JA (2006) Immigrants on the Isle of Lewis—combining traditional funerary and modern isotope evidence to investigate social differentiation, migration and dietary change in the outer Hebrides of Scotland. In: Gowland R, Knusel C (eds) The social archaeology of funerary remains. Oxbow Books, Oxford, pp 122–142

Montgomery J, Evans JA, Horstwood MSA (2010) Evidence for long-term averaging of strontium in bovine enamel using TIMS and LA-MC-ICP-MS strontium isotope intra-molar profiles. Environ Archaeol 15:32–42

Müller W, Fricke H, Halliday AN, McCulloch MT, Wartho JA (2003) Origin and migration of the alpine iceman. Science 302:862–866

Müller-Scheeßel N, Grupe G, Tütken T (2015) In der Obhut von Verwandten? Die Zirkulation von Kindern und Jugendlichen in der Eisenzeit Mitteleuropas. In: Karl R, Leskovar J (eds) Interpretierte Eisenzeiten. Fallstudien, Methoden, Theorie. Studien zur Kulturgeschichte von Oberösterreich. Oberösterreichisches Landesmuseum, Linz, Österreich, pp 9–24

Murphy EM (2017) Ten years of childhood in the past. Childhood in the Past 10:1–9

Nowell GM, Horstwood MSA (2009) Comments on Richards et al., Journal of Archaeological Science 35, 2008 "Strontium isotope evidence of Neanderthal mobility at the site of Lakonis, Greece using laser-ablation PIMMS". J Archaeol Sci 36:1334–1341

Parkes P (2006) Celtic fosterage: adoptive kinship and clientage in Northwest Europe. Comp Stud Soc Hist 48:359–395

Patterson O (1982) Slavery and social death: a comparative study. Harvard University Press, Cambridge, MA

Price TD, Bentley RA, Lüning J, Gronenborn D, Wahl J (2001) Prehistoric human migration in the Linearbandkeramik of Central Europe. Antiquity 75:593–603

Price TD, Burton JH, Bentley RA (2002) The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. Archaeometry 44:117–135

Price TD, Burton JH, Stoltman JB (2007) Place of origin of prehistoric inhabitants of Aztalan, Jefferson co., Wisconsin. Am Antiq 72(3): 524–538

Richards M, Harvati K, Grimes V, Smith C, Smith T, Hublin JJ, Karkanas P, Panagopoulou E (2008) Strontium isotope evidence of Neanderthal mobility at the site of Lakonis, Greece using laser-ablation PIMMS. J Archaeol Sci 35:1251–1256

Scheeres M (2014) High mobility rates during the period of the "Celtic migrations"? 87Sr/86Sr and δ18O evidence from Early La Tène Europe. Dissertation, Johannes Gutenberg–Universität Mainz

Scheeres M, Knipper C, Hauschild M, Schönfelder M, Siebel W, Vitali D, Pare C, Alt KW (2013) Evidence for "Celtic migrations"? Strontium isotope analysis at the early La Tène (LT B) cemeteries of Nebringen (Germany) and Monte Bibele (Italy). J Archaeol Sci 40:3614–3625

Scheeres M, Knipper C, Hauschild M, Schönfelder M, Siebel W, Pare C, Alt KW (2014) "Celtic migrations": fact or fiction? Strontium and oxygen isotope analysis of the Czech cemeteries of Radovesice and Kutná Hora in Bohemia. Am J Phys Anthropol 155:496–512

Schweissing MM, Grupe G (2003) Tracing migration events in man and cattle by stable strontium isotope analysis of appositionally grown mineralized tissue. Int J Osteoarchaeol 13:96–103

Sieff DF (1997) Herding strategies of the Datoga pastoralists of Tanzania: is household labor a limiting factor. Hum Ecol 25:519–544

Slater PA, Hedman KM, Emerson TE (2014) Immigrants at the Mississippian polity of Cahokia: strontium isotope evidence for population movement. J Archaeol Sci 44:117–127

Slovak NM, Paytan A (2011) Applications of Sr isotopes in archaeology. In: Baskaran M (ed) Handbook of environmental isotope geochemistry, I edn. Springer. Berlin Heidelberg, Berlin, Heidelberg, pp 743–768

Spier L (1928) Havasupai ethnography. Anthropological Papers of the American Museum of Natural History. Am Anthropol 29:81–408

Spittler G (2012) Children's work in a family economy: a case study and theoretical discussion. In: Spittler G, Bourdillon MFC (eds) African children at work: working and learning in growing up for life. LIT Verlag, Berlin, pp 57–85

Thompson AR, Hedman KM, Slater PA (2015) New dental and isotope evidence of biological distance and place of origin for mass burial groups at Cahokia's mound 72. Am J Phys Anthropol 158:341–357

Tung TA, Knudson KJ (2011) Identifying locals, migrants, and captives in the Wari heartland: a bioarchaeological and biogeochemical study of human remains from Conchopata, Peru. J Anthropol Archaeol 30:247–261

Weber AW, Goriunova OI (2013) Hunter-gatherer migrations, mobility and social relations: a case study from the Early Bronze Age Baikal region, Siberia. J Anthropol Archaeol 32:330–346

Wemple SF (1993) Consent and dissent to sexual intercourse in Germanic societies from the fifth to the tenth century. In: Laiou AE (ed) Consent and coercion to sex and marriage in ancient and medieval societies. Dumbarton Oaks Research Library and Collection, Washington, D.C., pp 227–243

Whiting BB, Edwards CP (1988) Children of different worlds: the formation of social behavior. Hardvard University Press, Cambridge, MA

Wright LE (2005) Identifying immigrants to Tikal, Guatemala: defining local variability in strontium isotope ratios of human tooth enamel. J Archaeol Sci 32:555–566