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Citation

Kootker, L. M., & Laffoon, J. E. (2022). Assessing the preservation of biogenic strontium isotope ratios (Sr-87/Sr-86) in the pars petrosa ossis temporalis of unburnt human skeletal remains: a case study from Saba. *Rapid Communications In Mass Spectrometry*, 36(10). doi:10.1002/rcm.9277

Version: Publisher's Version

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Note: To cite this publication please use the final published version (if applicable).

RESEARCH ARTICLE

Assessing the preservation of biogenic strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) in the pars petrosa ossis temporalis of unburnt human skeletal remains: A case study from Saba

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Funding information

ERC-Synergy project NEXUS1492, Grant/Award Number: FP7/2007-2013; ERC, Grant/Award Number: 319209

Rationale: Strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) analysis of skeletal remains has become a powerful tool in archaeological studies of human migration and mobility. Owing to its resistance to post-mortem alteration, dental enamel is the preferred sampling material used for $^{87}\text{Sr}/^{86}\text{Sr}$ analysis in bioarchaeological provenance research, although recent studies have demonstrated that cremated bone is also generally resistant to diagenesis. This paper presents the results of a pilot study exploring the potential of unburnt petrous bone (pars petrosa) as a reservoir of biogenic (diagenetically unaltered) strontium, as the otic capsule or bony labyrinth within the petrous bone is extremely dense and is thought to be unable to remodel after early childhood, potentially providing an alternative for dental enamel.

Methods: From an individual from a colonial-era (18th century) site on the island of Saba in the Caribbean for whom previous enamel $^{87}\text{Sr}/^{86}\text{Sr}$ results had indicated non-local origins, multiple locations ($n = 4$) on the petrous were sampled and measured for strontium isotope composition. Saba (13 km²) has been extensively mapped for baseline strontium isotopes ($n = 50$) with $^{87}\text{Sr}/^{86}\text{Sr}$ varying from ca 0.7065 to 0.7090, whereas enamel $^{87}\text{Sr}/^{86}\text{Sr}$ ($n = 3$) ranged from 0.7104 to 0.7112.

Results: All four petrous $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7111–0.7122) are consistently and considerably higher than the local bioavailable range, and very similar to the enamel $^{87}\text{Sr}/^{86}\text{Sr}$. These results provide initial evidence that unburnt petrous bones may preserve biogenic strontium, at least in this specific burial context.

Conclusions: While more research in diverse burial conditions is needed to validate this observation, if confirmed, it would have broader implications for sample selection strategies in bioarchaeological studies using the strontium isotope method.

1 | INTRODUCTION

The human pars petrosa ossis temporalis has become the ‘Holy Grail’ in ancient DNA studies since pioneering research by Pinhasi et al in 2015 showed that relatively elevated quantities of high-quality endogenous aDNA were preserved in the bony otic capsule of the

inner ear.¹ Recently, the otic capsule, or bony labyrinth, has proven to be valuable in archaeological isotope studies as well.² Due to their increased crystallinity, cremated or calcined archaeological skeletal remains have proven to exhibit the diagenetically unaltered, i.e. original or biogenic, strontium isotope composition ($^{87}\text{Sr}/^{86}\text{Sr}$) at the time of death.^{3–5} Due to the extremely slow remodelling rate of

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the otic capsule compared to the surrounding bone of the petrous or other bones in the skeleton,^{6–8} the bony labyrinth of cremated petrous portions (PP) is nowadays considered the equivalent of dental enamel and thus a reliable proxy for the geochemical environment of infancy. As such, calcined otic capsules can be effectively used to provide insights into the childhood (geographical) provenance of cremated burials for which dental enamel is often not well preserved or recovered.^{8–10}

However, to date, little research has been conducted on the applicability of the pars petrosa or otic capsule in unburnt archaeological skeletal assemblages for provenance studies in cases where dental elements are absent. A major problem in isotopic studies on the apatite component of bone, however, is the process of diagenesis.¹¹ The post-mortem chemical and physical changes that happen to a bone during burial have a negative and irreversible impact on the biogenic strontium isotope composition of bone bioapatite. In contrast to the porous structure of bone, the otic capsule is the densest bone in the human skeleton¹² and therefore considered to be less prone to diagenetic alterations.

To investigate the effect of diagenesis on the biogenic ⁸⁷Sr/⁸⁶Sr of the otic capsule of unburnt pars petrosae, and its applicability for provenance studies, a unique case study was investigated. In this study the ⁸⁷Sr/⁸⁶Sr¹³ and Sr concentrations of enamel and dentine samples from three molars and of one pars petrosa are presented from an inhumed female from a historic period site on the island of Saba, a special municipality of the Netherlands in the northeast Caribbean. Based on the archaeological, osteoarchaeological and isotopic evidence (elevated, non-local ⁸⁷Sr/⁸⁶Sr), this individual was interpreted as an individual of African origin, who was enslaved and forced to migrate to Saba in the late 18th century.¹³ The strontium isotope difference between the region of childhood origin (Africa) and the location of death (Saba) is immense. The bioavailable strontium isotope range on Saba (mean: 0.7083; range: 0.7065–0.7090) is much lower than that in much of West and West-Central Africa, which is underlain by diverse geological formations including large areas of continental bedrock (including cratonic formations) with highly variable but generally higher ⁸⁷Sr/⁸⁶Sr (greater than *ca* 0.710).¹⁴ Consequently, a diagenetic shift in the otic capsule's ⁸⁷Sr/⁸⁶Sr towards the Saba range should be apparent if the otic capsule is affected by diagenesis. This paper presents the results of this pioneering study and provides directions for future research on the use of unburnt pars petrosae in archaeological mobility studies.

2 | DIAGENESIS IN PALAEO MOBILITY STUDIES

The effects of diagenesis on the isotopic integrity of archaeological bone and dentine have been the subject of research for the past few decades. Nearly four decades ago, when strontium isotope analysis was first introduced to the field of human biomolecular archaeology,^{15,16} the complicating effects of diagenesis were already acknowledged.^{17,18} In the 1980s, decontamination of (bone) tissue

was thought to be accomplished through 'mechanical excoriation, tissue separation, and phase separation by chemical reaction' with acetic acid.^{16,19,20} Nevertheless, convincing evidence of diagenetic alteration of bone chemistry and strontium isotope composition was provided shortly after in 1986 by Nelson and colleagues and confirmed by many studies thereafter.^{21–24}

Many early studies of human palaeomobility based on strontium isotope analysis focused on sampling of enamel and bone.^{16,25–28} Over time, more evidence accumulated demonstrating the higher susceptibility of bone and dentine to diagenesis (relative to enamel) generally, and post-mortem alteration of biogenic strontium isotope signals more specifically.^{21,22,29} Owing to this, bone has become slowly abandoned as a suitable sampling material in most strontium isotope studies of palaeomobility over the last two decades. Nevertheless, some studies continued to analyse bone and dentine strontium isotope signals as proxies of the local range of bioavailable ⁸⁷Sr/⁸⁶Sr under the debatable assumption that these sampling materials should be reflective of local diagenetic ⁸⁷Sr/⁸⁶Sr^{30,31} or that all diagenetic contaminants were successfully removed.³²

Until several years ago, dental enamel was considered the only suitable sampling material for archaeological palaeomobility and provenance studies owing to the fact that it does not undergo remodelling once fully mineralized and that it is generally resistant to post-mortem isotopic alteration. A study by Jørkov and colleagues,² however, highlighted the point that the otic capsule of the petrous portion of the temporal bone is also a suitable proxy for stable isotope studies of the early dietary patterns similar to enamel, as it does not appear to undergo remodelling once fully formed in infancy/early childhood. After pioneering experimental research by Harbeck et al,³ another experimental study by Snoeck et al⁵ convincingly demonstrated that the process of cremation at high temperatures (calcination) does not alter biogenic ⁸⁷Sr/⁸⁶Sr, and opened up the strontium isotope method to be applied to cremated remains in archaeological contexts.^{9,10,33–35}

In fact, the first application of strontium isotope analyses to PP by Harvig et al obtained ⁸⁷Sr/⁸⁶Sr in both cremated and inhumed skeletal remains to assess the reliability of the petrous as a sampling element for strontium isotope mobility studies.⁴ To our knowledge, this study represents the only study conducted to date to measure ⁸⁷Sr/⁸⁶Sr in unburnt PP.⁴ Owing to the high degree of correlation between (premolar) enamel and petrous ⁸⁷Sr/⁸⁶Sr signatures obtained from the same individuals, for both cremated and inhumed remains, the authors concluded that biogenic strontium is retained in archaeological petrous samples and is indicative of childhood origins.⁴ However, although their study apparently included two individuals of non-local origins, most of the sampled individuals were of local origins. Additionally, premolar enamel crowns develop and mineralize from roughly 2 to 6 years of age after the remodelling of the otic capsule is believed to cease, and thus it is difficult to assess if differences in ⁸⁷Sr/⁸⁶Sr between petrous bone and premolar enamel samples reflect age-related changes or diagenesis of the former. Furthermore, their study reported the range of bioavailable ⁸⁷Sr/⁸⁶Sr at the national level (Denmark), whereas the local (site) bioavailable

4 | MATERIALS AND METHODS

4.1 | Materials

A more detailed description of the site and the osteoarchaeological data of the middle adult (36- to 45-year-old) female and the *ca* 34- to 40-week-old foetus is given in Fricke et al.¹³ For this study, the right PP of the adult female was selected for Sr isotope research; the left specimen was of better quality and therefore saved for future aDNA research. The PP was cut through its central axis to create a midmodiolar section through the cochlea using a Buehler (Esslingen, Germany) IsoMet 1000 precision saw. Following the optimized sampling strategy of Veselka et al.,⁸ two samples of the cochlea and one of the semicircular canal were taken. In addition, a reference bone sample was collected from an area that is not part of the otic capsule and as such was subject to remodelling during life. The quality of the PP of the foetus was poor and did not allow the PP to be cut midmodiolarly. Instead, the outer surface of the PP was mechanically cleaned, and a random bone sample was taken. In addition to the PP bone samples and the previously published enamel samples from the individual,¹³ three dentine samples were taken from the same three teeth (36, 47 and 28). The tooth roots were mechanically cleaned prior to removal of the dentine samples from the exterior surface of the middle section of the root.

All bone and dentine samples were taken at the Archaeological and Forensic sample preparation laboratory at the Vrije Universiteit Amsterdam using a Proxxon drill equipped with a ball-shaped diamond-coated grinding bit and collected in clean glass vials. After each sample, the drill bit was cleaned in Milli-Q water, 10% HCl and ethanol to prevent inter-sample contamination. The samples were collected in 6–7 M HCl-cleaned 2.0 mL Eppendorf® tubes and transferred to the US Federal Standard Class 100 (ISO5) clean laboratory facility at the Vrije Universiteit Amsterdam for Sr purification.

4.2 | Isotope analysis

Strontium column extraction and sample loading were performed following previously published protocols.⁴² The isotope compositions were measured using a Thermo Scientific™ Triton Plus™ instrument housed at the Vrije Universiteit Amsterdam, the Netherlands. The strontium ratios were determined using a static routine and were corrected for mass fractionation to $^{86}\text{Sr}/^{88}\text{Sr}$ of 0.1194.⁴³ The NIST® SRM® 987 Strontium Carbonate reference material gave an average of 0.710258 ± 0.000008 (2s) during the course of this study ($n = 77$). The intermediate precision over the period 2017–2021 using this method was 0.710254 ± 0.000018 (2s; $n = 433$). All measurements were normalized to an accepted value of 0.710240 for SRM 987. The total procedural blanks ($n = 5$) contained between 28 and 52 pg of strontium. The $^{87}\text{Sr}/^{86}\text{Sr}$ values are reported plus or minus two standard error (2SE), representing the typical measurement precision obtained from 240 cycles of 8.1 s integration time (12 blocks of 20 cycles) within each run.

4.3 | Concentration measurements

Between 1.3 and 4.1 mg of dentine and enamel powder was transferred into acid-purified inductively coupled plasma tubes, and diluted with 10% HNO₃ (dilution factor 4500–5500). The acidified samples were measured using a Thermo X-Series II inductively coupled plasma mass spectrometer at the Vrije Universiteit Amsterdam, the Netherlands. The aliquot solutions were introduced via a quartz dual cyclonic spray chamber equipped with a PFA-ST MicroFlow nebulizer (Elemental Scientific) with a sample uptake rate of about 100 $\mu\text{L min}^{-1}$. Changes in sensitivity over time were monitored and corrected for using the geological reference material BHVO-2, which was measured after every second sample (modified after Eggins et al.⁴⁴). Strontium concentrations were calculated using a two-point calibration of blank and BHVO-2. The intermediate precision determined with multiple geological reference materials was about 10% (2s).

5 | RESULTS

The results of the strontium isotope analysis and concentration measurements are provided in Table 1 and Figure 2. The three samples collected from the petrous part's otic capsule in the female (individual 1) all provide similar $^{87}\text{Sr}/^{86}\text{Sr}$, ranging between 0.7111 and 0.7113. The sample taken from a randomly chosen location within the petrous part exhibits a more radiogenic strontium isotope composition: 0.7123. None of these data are compatible with the bioavailable strontium isotope range of Saba.^{36,41} On the contrary, the $^{87}\text{Sr}/^{86}\text{Sr}$ of the randomly selected petrous sample of the foetus (0.7086) matches well with the local $^{87}\text{Sr}/^{86}\text{Sr}$ (median: 0.7084). The strontium isotope compositions of the dentine samples are similar to the previously published dental enamel data (0.7105–0.7112¹³), i.e. much more radiogenic than the Saba signature, ranging from 0.7096 in the M1 (36) to 0.7116 in the M3 (38). The dental strontium concentration data fluctuate between 201 and 345 ppm in enamel and 332 and 427 ppm in dentine, with the dentine Sr concentration generally being higher.

6 | DISCUSSION

Since the strontium isotope ratios of all three dental enamel samples are significantly higher than the local range, this suggests that the proposed transatlantic migration occurred after childhood (after formation of the third molar enamel which is completed around 11–16 years of age^{45,46}). However, the $^{87}\text{Sr}/^{86}\text{Sr}$ of the third molar enamel is somewhat elevated relative to that of the first and second molar enamel samples. In a previous study this was tentatively suggested to indicate a possible prior migration event in adolescence, perhaps within Africa.¹³

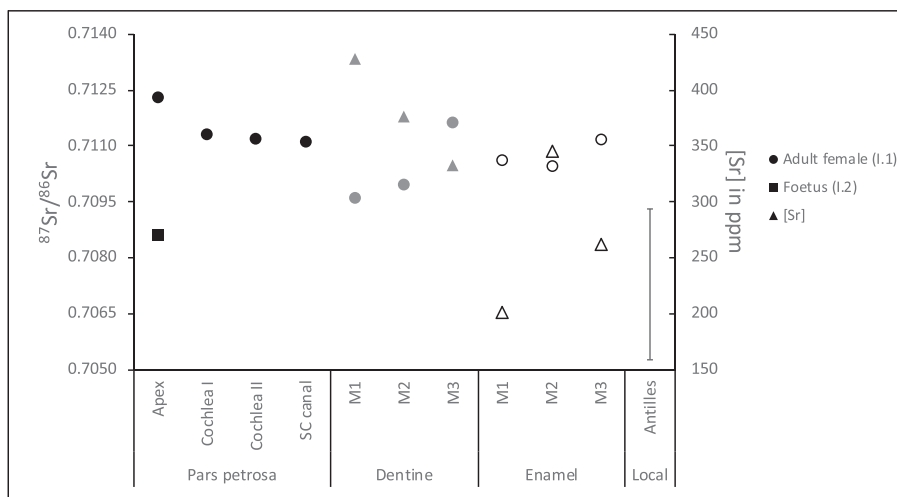
The strontium concentrations in the dentine sample increased between 9% in the M2 (27) to 112% in the M1 (26) compared to the

TABLE 1 Strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) of enamel, dentine and petrous samples; and strontium concentrations of enamel and dentine samples^a

| ID | Sex | Age at death | Material | Element | Sample | $^{87}\text{Sr}/^{86}\text{Sr}$ | 2SE | [Sr] (ppm) |
|--------------|--------|----------------------|---------------------|---------|--------------------|---------------------------------|----------|------------|
| Individual 1 | Female | 36–45 years | Bone | PP | Cochlea | 0.711202 | 0.000007 | – |
| | | | | | Cochlea II | 0.711320 | 0.000008 | – |
| | | | | | Semicircular canal | 0.711118 | 0.000007 | – |
| | | | | | Apex | 0.712292 | 0.000009 | – |
| | | | Enamel ^b | Molar | 36 | 0.710630 | 0.000011 | 201 |
| | | | | | 47 | 0.710450 | 0.000011 | 345 |
| | | | | | 28 | 0.711170 | 0.000010 | 262 |
| | | | Dentine | Molar | 36 | 0.709572 | 0.000008 | 427 |
| | | | | | 47 | 0.709962 | 0.000009 | 375 |
| | | | | | 28 | 0.711633 | 0.000008 | 332 |
| Individual 2 | – | 34 weeks <i>i.u.</i> | Bone | PP | Random | 0.708611 | 0.000008 | – |

^aPP, petrous part; 2SE, 2 standard error; [Sr], strontium concentration; *i.u.*, in utero.

^bData from Fricke et al.¹³

FIGURE 2 Strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) of enamel, dentine and petrous samples, and strontium concentrations [Sr] of enamel and dentine samples from individuals 1 and 2 from Saba. Key: SC canal, semicircular canal; M1, first molar; M2, second molar; M3, third molar

enamel samples from the same dental element. Since the Sr concentrations in dentine and enamel are similar during life (see Supporting Information - Data S1), the increase in Sr concentrations is considered to reflect partial incorporation of diagenetic Sr. For the first and second molars, dentine samples possess higher Sr concentrations and lower $^{87}\text{Sr}/^{86}\text{Sr}$ that are intermediate between the corresponding enamel and the median of the local bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$. This suggests that these dentine samples contain a mix of biogenic and diagenetic strontium. A slightly different pattern is observed for the third molar dentine sample, which has a Sr concentration that is slightly higher than that of the corresponding enamel sample (27%), but exhibits an $^{87}\text{Sr}/^{86}\text{Sr}$ that is actually more radiogenic than the third molar enamel $^{87}\text{Sr}/^{86}\text{Sr}$. If a diagenetic shift towards the local signature is assumed, the biogenic third molar dentine $^{87}\text{Sr}/^{86}\text{Sr}$ must have been even more radiogenic than 0.7116. This pattern suggests that the third molar dentine is not highly impacted by diagenesis, and lends further support to the notion that this individual may have undergone a previous migration that

occurred subsequent to the mineralization of the third molar enamel and during the formation of the third molar root dentine. As third molar roots generally start to develop during late childhood and finish forming at approximately 20 years of age, this may indicate that this purported earlier migration event occurred as an adolescent or young adult. As both the M3 enamel and dentine $^{87}\text{Sr}/^{86}\text{Sr}$ are highly elevated relative to the bioavailable range for the Antilles, this also suggests that this earlier (forced) migration within the African continent occurred prior to the later forced migration to the Caribbean.

The $^{87}\text{Sr}/^{86}\text{Sr}$ of the three samples collected from the adult female's otic capsule are substantially higher than the bioavailable strontium signature at the location of burial, and broadly comparable to the $^{87}\text{Sr}/^{86}\text{Sr}$ of the enamel samples. In fact, the strontium isotope composition of the three otic capsule samples is nearly identical to that of the third molar enamel (38) and not to that of the first molar enamel (26) as was expected based on the assumed age at which the PP is thought to stop remodelling (Figure 3). A possible explanation

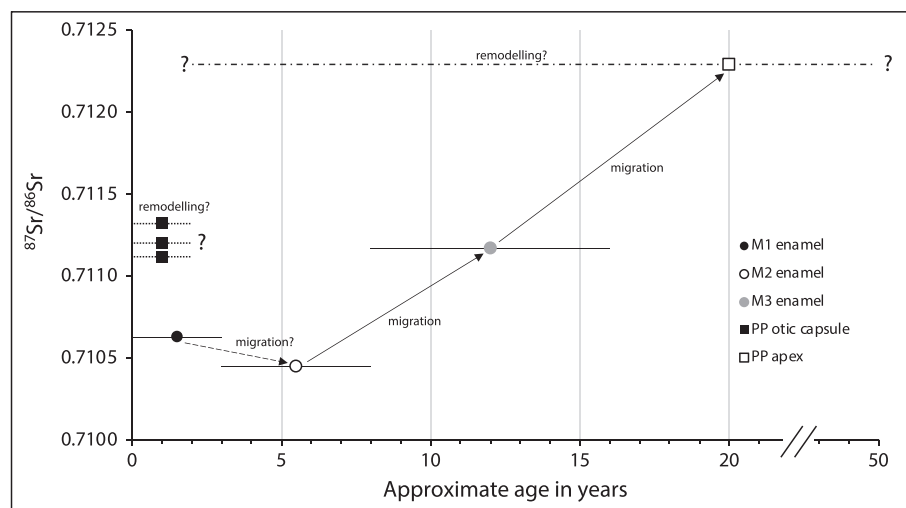


FIGURE 3 Strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) of enamel and petrous samples plotted relative to approximate age of formation/mineralization. The three otic capsule samples exhibit $^{87}\text{Sr}/^{86}\text{Sr}$ that are more consistent with the third molar (M3) than the first or second molars (M1 or M2), possibly indicating that they reflect a later time period rather than infancy. The single random sample of the petrous has a relatively elevated $^{87}\text{Sr}/^{86}\text{Sr}$ and owing to multiple confounding factors the period that is reflected by this sample is unknown

can be found in the autobiography of Individual 1. Fricke et al concluded that she may have suffered from leprosy or another infectious disease.¹³ Some infectious diseases can cause hearing impairment. For example, leprosy or certain viral infections can affect the cochlear system, possibly resulting in (abnormal) bone remodelling in the otic capsule.⁴⁷ Consequently, the otic capsule's $^{87}\text{Sr}/^{86}\text{Sr}$ may not be representative of the first few years of life as more recent $^{87}\text{Sr}/^{86}\text{Sr}$ will have been incorporated during this process, possibly resulting in higher $^{87}\text{Sr}/^{86}\text{Sr}$ more similar to that of the third molar's enamel. Notably, the petrous bone sample that was taken from the apex of the PP exhibits an even higher $^{87}\text{Sr}/^{86}\text{Sr}$ (0.71229), indicating an isotopic shift in the opposite direction of diagenesis. If we assume that this petrous sample (i.e. not from the otic capsule) of the adult undergoes remodelling throughout life, this indicates that this individual must have resided in a region characterized by more radiogenic strontium isotope ratios than the location where she resided in childhood that is recorded in her first and second molar enamel. If so, this lends further support to the two-migration scenario.

Lastly, the foetal petrous sample's $^{87}\text{Sr}/^{86}\text{Sr}$ falls within the local range of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ for the island of Saba. This result could reflect a purely biogenic strontium isotope signal, assuming that the foetal tissue reflects the diet of the mother who resided on Saba throughout her pregnancy. Alternatively, given the rather delicate nature and poor physical condition of the foetal petrous specimen, it may have been particularly susceptible to diagenesis. In the absence of other evidence, it is not possible to determine if the $^{87}\text{Sr}/^{86}\text{Sr}$ of the foetal petrous sample reflects biogenic strontium uptake, post-mortem diagenesis or some combination of these two processes.

7 | CONCLUSIONS

The results of this study highlight several important issues with broader relevance for sampling and research design strategies concerning isotope studies of palaeomobility. The pronounced

variation in dentine $^{87}\text{Sr}/^{86}\text{Sr}$ recorded within different dental elements of a single individual suggests that dentine is not a suitable sampling material for assessing the local range of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$. Although more time-consuming, expensive and labour-intensive, sampling of local biosphere samples or archaeological rodents for strontium isotope analyses provides a more reliable and independent assessment of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ variation. As long advocated by several research groups, analysis of Sr concentrations (in conjunction with Sr isotope analysis) can provide important complementary information for interpreting strontium isotope data obtained from archaeological skeletal remains and is particularly effective for assessing differential diagenesis. The sampling of multiple tissues and different dental elements can provide much more information concerning the age at which migrations occurred and more insight into individual life histories than sampling strategies that focus solely on a single isotope analysis per individual.

The results of this study provide strong evidence that unaltered, biogenic $^{87}\text{Sr}/^{86}\text{Sr}$ is retained in (unburnt) pars petrosa; at least in this particular archaeological burial context. It is, however, important to study the osteological biography of the individuals in detail prior to analysis. Different diseases or conditions, such as leprosy, osteoporosis and otosclerosis, may result in hearing loss of cochlear origin, possibly due to remodelling or demineralisation of the otic capsule.⁴⁷⁻⁴⁹ Consequently, the otic capsule's $^{87}\text{Sr}/^{86}\text{Sr}$ may not be fully representative of the early years of life.

Perhaps the most unexpected result of this study was that a sample taken from a random portion of the petrous, outside of the otic capsule, not only seems to possess a biogenic $^{87}\text{Sr}/^{86}\text{Sr}$ but that this enriched $^{87}\text{Sr}/^{86}\text{Sr}$ signal is consistent with that of the M3 dentine and tentatively supports the identification of a previous migration occurring after childhood but prior to the forced migration from Africa to the Caribbean. This is consistent with the historical data showing that in the mid-18th century the transatlantic slave trade intensified and increasing numbers of individuals were taken captive in the interior of West and West-Central Africa and later brought to coastal ports for subsequent sale and transshipment

across the Atlantic (see Trans-Atlantic Slave Trade database at slavevoyages.org).

To be clear, we are not advocating that the otic capsule, or the pars petrosa, of inhumed remains are ideal sampling targets for strontium isotope analyses of archaeological skeletal remains. However, the results of this study support the main conclusions of a previous study⁴ indicating that biogenic ⁸⁷Sr/⁸⁶Sr may be retained in inhumed pars petrosa in certain archaeological contexts. Although we expect that dental enamel will remain the preferred sampling material for most isotope studies of human palaeomobility, the pars petrosa may provide an alternative sampling element in cases where teeth are not preserved or are otherwise unavailable for analyses, and can potentially be sampled in conjunction with aDNA studies which increasingly target this skeletal element anyway. Although the results of the present study and those of the previous study from Harvig and colleagues⁴ seem promising, it is necessary to conduct more research into differential diagenesis in a wider range of archaeological burial contexts before strontium isotope analysis of inhumed pars petrosa can be more broadly applied in archaeological palaeomobility studies.

ACKNOWLEDGEMENTS

The authors are grateful to the Nexus1492 excavation team and the Saba Archaeological Centre (SABARC) for granting access to the skeletal materials for analyses. Dr Kirsten van Zuilen, Vrije Universiteit Amsterdam, is thanked for generating the inductively coupled plasma mass spectrometry data (supporting information). This project was funded through the ERC-Synergy project NEXUS1492, from the European Research Council under the EU's 7th Framework Programme (FP7/2007-2013) / ERC grant agreement no. 319209.

DATA AVAILABILITY STATEMENT

The archaeological isotope data are available in this paper and Fricke et al¹³ and are shared in the open access and collaborative isotope database IsoArch (isoarch.eu).⁵⁰

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REFERENCES

- Pinhasi R, Fernandes D, Sirak K, et al. Optimal ancient DNA yields from the inner ear part of the human petrous bone. *PLoS ONE*. 2015; 10(6):e0129102. doi:10.1371/journal.pone.0129102
- Jørkov MLS, Heinemeier J, Lynnerup N. The petrous bone—A new sampling site for identifying early dietary patterns in stable isotopic studies. *Am J Phys Anthropol*. 2009;138(2):199-209. doi:10.1002/ajpa.20919
- Harbeck M, Schleuder R, Schneider J, Wiechmann I, Schmahl WW, Grupe G. Research potential and limitations of trace analyses of cremated remains. *Forensic Sci Int*. 2011;204(1-3):191-200. doi:10.1016/j.forsciint.2010.06.004
- Harvig L, Frei KM, Price TD, Lynnerup N. Strontium isotope signals in cremated petrous portions as indicator for childhood origin. *PLoS ONE*. 2014;9(7):e101603. doi:10.1371/journal.pone.0101603
- Snoeck C, Lee-Thorp J, Schulting R, de Jong J, Debouge W, Mattielli N. Calcined bone provides a reliable substrate for strontium isotope ratios as shown by an enrichment experiment. *Rapid Commun Mass Spectrom*. 2015;29(1):107-114. doi:10.1002/rcm.7078
- Sørensen MS. Temporal bone dynamics, the hard way. Formation, growth, modeling, repair and quantum type bone remodeling in the otic capsule. *Acta Otolaryngol Suppl*. 1994;512:1-22.
- Frisch T, Sørensen MS, Overgaard S, Bretlau P. Estimation of volume referent bone turnover in the otic capsule after sequential point labeling. *Ann Otol Rhinol Laryngol*. 2000;109:33-39. doi:10.1177/000348940010900106
- Veselka B, Locher H, De Groot J, Davies GR, Snoeck C, Kootker LM. Strontium isotope ratios related to childhood mobility: Revisiting sampling strategies of the calcined human pars petrosa ossis temporalis. *Rapid Commun Mass Spectrom*. 2021;35(7):e9038. doi:https://doi.org/10.1002/rcm.9038
- Veselka B, Capuzzo G, Annaert R, et al. Divergence, diet, and disease: The identification of group identity, landscape use, health, and mobility in the fifth-to sixth-century AD burial community of Echt, the Netherlands. *Archaeol Anthropol Sci*. 2021;13(6):97. doi:10.1007/s12520-021-01348-7
- Cavazzuti C, Cardarelli A, Quondam F, et al. Mobile elites at Frattesina: Flows of people in a late bronze age 'port of trade' in northern Italy. *Antiquity*. 2019;93(369):624-644. doi:10.15184/aqy.2019.59
- Hedges REM. Bone diagenesis: An overview of processes. *Archaeometry*. 2002;44(3):319-328. doi:10.1111/1475-4754.00064
- Bast TH, Anson BJ. *The temporal bone and the ear*. Springfield, IL: Charles C. Thomas; 1949.
- Fricke F, Laffoon J, Espersen R. Unforgotten: The osteobiography of an enslaved woman and child from 18th century Saba. *J Archaeol Sci Rep*. 2021;36:102838.
- Schroeder H, O'Connell TC, Evans JA, Shule KA, Hedges REM. Trans-Atlantic slavery: Isotopic evidence for forced migrations. *Am J Phys Anthropol*. 2009;139(4):547-557. doi:10.1002/ajpa.21019
- Ericson JE. Strontium isotope characterization. Proceedings of the Society for Archaeological Sciences (Abstract). 1980.
- Ericson JE. Strontium isotope characterization in the study of prehistoric human ecology. *J Hum Evol*. 1985;14(5):503-514. doi:10.1016/S0047-2484(85)80029-4
- Ericson JE, Shirahata H, Patterson CC. Skeletal concentrations of lead in ancient Peruvians. *N Engl J Med*. 1979;300(17):946-951. doi:10.1056/NEJM197904263001703
- Price TD, Blitz J, Burton J, Ezzo JA. Diagenesis in prehistoric bone: Problems and solutions. *J Archaeol Sci*. 1992;19(5):513-529. doi:10.1016/0305-4403(92)90026-Y
- Sillen A. Biogenic and diagenetic Sr/ca in Plio-Pleistocene fossils in the Omo Shungura formation. *Paleobio*. 1986;12:311-323. doi:10.1017/S0094837300013816
- Price TD, Johnson CM, Ezzo JA, Ericson J, Burton JH. Residential-mobility in the prehistoric Southwest United-States -a preliminary-study using strontium isotope analysis. *J Archaeol Sci*. 1994;21(3):315-330. doi:10.1006/jasc.1994.1031
- Budd P, Montgomery J, Barreiro B, Thomas RG. Differential diagenesis of strontium in archaeological human dental tissues. *Appl Geochem*. 2000;15:687-694. doi:10.1016/S0883-2927(99)00069-4
- Trickett MA, Budd P, Montgomery J, Evans J. An assessment of solubility profiling as a decontamination procedure for the ⁸⁷Sr/⁸⁶Sr analysis of archaeological human skeletal tissue. *Appl Geochem*. 2003; 18(5):653-658. doi:10.1016/S0883-2927(02)00181-6
- Hoppe KA, Koch PL, Furutani TT. Assessing the preservation of biogenic strontium in fossil bones and tooth enamel. *Int J Osteoarchaeol*. 2003;13(1-2):20-28. doi:10.1002/oa.663
- Nelson BK, Deniro MJ, Schoeninger MJ, De Paolo DJ, Hare PE. Effects of diagenesis on strontium, carbon, nitrogen and oxygen

- concentration and isotopic composition of bone. *Geochim Cosmochim Acta*. 1986;50(9):1941-1949. doi:10.1016/0016-7037(86)90250-4
25. Price TD, Knipper C, Grupe G, Smrcka V. Strontium isotopes and prehistoric human migration: The bell beaker period in Central Europe. *Eur J Archaeol*. 2004;7(1):9-40. doi:10.1177/1461957104047992
 26. Price TD, Bentley RA, Lüning J, Gronenborn D, Wahl J. Prehistoric human migration in the Linearbandkeramik of Central Europe. *Antiquity*. 2001;75(289):593-603. doi:10.1017/S0003598X00088827
 27. Schweissing MM, Grupe G. Stable strontium isotopes in human teeth and bone: A key to migration events of the late Roman period in Bavaria. *J Archaeol Sci*. 2003;30(11):1373-1383. doi:10.1016/S0305-4403(03)00025-6
 28. Schweissing MM, Grupe G. Local or nonlocal? A research of strontium isotope ratios of teeth and bones on skeletal remains with artificial deformed skulls. *Anthropol Anz*. 2000;58:99-103. doi:10.1127/anthranz/58/2000/99
 29. King CL, Tayles N, Gordon KC. Re-examining the chemical evaluation of diagenesis in human bone apatite. *J Archaeol Sci*. 2011;38(9):2222-2230. doi:10.1016/j.jas.2011.03.023
 30. Triantaphyllou S, Nikita E, Kador T. Exploring mobility pattern and biological affinities in the southern Aegean: First insights from early bronze age eastern Crete. *Annu Br Sch Athens*. 2015;110:3-25. doi:10.1017/S0068245415000064
 31. Nafplioti A. Tracing population mobility in the Aegean using isotope geochemistry: A first map of local biologically available $^{87}\text{Sr}/^{86}\text{Sr}$ signatures. *J Archaeol Sci*. 2011;38(7):1560-1570. doi:10.1016/j.jas.2011.02.021
 32. Lengfelder F, Grupe G, Stallauer A, Huth R, Söllner F. Modelling strontium isotopes in past biospheres –assessment of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in local archaeological vertebrates based on environmental signatures. *Sci Total Environ*. 2019;648:236-252. doi:10.1016/j.scitotenv.2018.08.014
 33. Snoeck C, Pouncett J, Claeys P, et al. Strontium isotope analysis on cremated human remains from Stonehenge support links with West Wales. *Sci Rep*. 2018;8(1):10790. doi:10.1038/s41598-018-28969-8
 34. Sabaux C, Veselka B, Capuzzo G, et al. Multi-proxy analyses reveal regional cremation practices and social status at the late bronze age site of Herstal, Belgium. *J Archaeol Sci*. 2021;132:105437. doi:10.1016/j.jas.2021.105437
 35. Reiter SS, Møller NA, Nielsen BH, et al. Into the fire: Investigating the introduction of cremation to Nordic bronze age Denmark: A comparative study between different regions applying strontium isotope analyses and archaeological methods. *PLoS ONE*. 2021;16(5):e0249476. doi:10.1371/journal.pone.0249476
 36. Laffoon JE, Hoogland MLP. Migration and mobility in the circum-Caribbean: Integrating archaeology and isotopic analysis. *Population Dynamics in Prehistory and Early History: New Approaches Using Stable Isotopes and Genetics*. In: Kaiser E, Burger J, Schier W, eds.: De Gruyter; 2012:337-354. 10.1515/9783110266306.337
 37. Bataille CP, Laffoon J, Bowen GJ. Mapping multiple source effects on the strontium isotopic signatures of ecosystems from the circum-Caribbean region. *Ecosphere*. 2012;3(12):art118. doi:10.1890/ES12-00155.1
 38. Laffoon JE, Sonnemann TF, Shafie T, Hofman CL, Brandes U, Davies GR. Investigating human geographic origins using dual-isotope ($^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{18}\text{O}$) assignment approaches. *PLoS ONE*. 2017;12(2):e0172562. doi:10.1371/journal.pone.0172562
 39. Laffoon JE, Valcárcel Rojas R, Hofman CL. Oxygen and carbon isotope analysis of human dental enamel from the Caribbean: Implications for investigating individual origins. *Archaeometry*. 2012;55(4):742-765. doi:10.1111/j.1475-4754.2012.00698.x
 40. Laffoon JE, Davies GR, Hoogland MLP, Hofman CL. Spatial variation of biologically available strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) in an archipelagic setting: A case study from the Caribbean. *J Archaeol Sci*. 2012;39(7):2371-2384. doi:10.1016/j.jas.2012.02.002
 41. Laffoon JE. *Patterns of paleomobility in the ancient Antilles: an isotopic approach*. Leiden: Faculty of Archaeology, Leiden University; 2012.
 42. Kootker LM, Mbeki L, Morris AG, Kars H, Davies GR. 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*. 2016;11(6):e0157750. doi:10.1371/journal.pone.0157750
 43. Nier AO. The coefficient of thermal diffusion of methane. *Phys Rev*. 1939;56(10):1009-1013. doi:10.1103/PhysRev.56.1009
 44. Eggins SM, Woodhead JD, Kinsley LPJ, et al. A simple method for the precise determination of ≥ 40 trace elements in geological samples by ICPMS using enriched isotope internal standardisation. *Chem Geol*. 1997;134(4):311-326. doi:10.1016/S0009-2541(96)00100-3
 45. Liversidge HM. *Dental age revisited. Technique and application in dental anthropology*. Cambridge: Cambridge University Press; 2008.
 46. Nelson SJ, Ash MM. *Wheeler's dental anatomy, physiology, and occlusion*. 9th ed. St. Louis, Missouri: Saunders Elsevier; 2010.
 47. Rawlani S, Patil CY, Bhowte R, et al. Evaluation of hearing impairment in leprosy patients taking multidrug therapy. *Indian J Lepr*. 2013;85:171-176.
 48. Handoko E, Murdiyo MD, Soesanto H. The difference of otic capsule density, auditory ossicles density, and hearing threshold in osteoporosis and non-osteoporosis patients at Saiful Anwar public hospital 2017. *Bali Med J*. 2018;7(3): (Available online: 1 December 2018). 2018
 49. Bloch SL. On the biology of the bony otic capsule and the pathogenesis of otosclerosis. *Dan Med J*. 2012;59:B4524
 50. Salesse K, Fernandes R, de Rochefort X, Brůžek J, Castex D, Dufour É. IsoArch.Eu: An open-access and collaborative isotope database for bioarchaeological samples from Graeco-Roman world and its margins. *J Archaeol Sci Rep*. 2018;19:1050-1055.

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How to cite this article: Kootker LM, Laffoon JE. Assessing the preservation of biogenic strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) in the pars petrosa ossis temporalis of unburnt human skeletal remains: A case study from Saba. *Rapid Commun Mass Spectrom*. 2022;36(10):e9277. doi:10.1002/rcm.9277