Mobility and the Landscape: Investigating mobility of individuals at Wadi Faynan 100 using minimally invasive strontium isotope analysis

by

Jessica A. Mah

A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Arts
in
Public Issues Anthropology

Waterloo, Ontario, Canada,
© Jessica A. Mah 2026

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

In comparison to other sites in Jordan, life at the Early Bronze Age (~3600-3000BC) site of Wadi Faynan 100 (WF100) is still largely a mystery. To better understand the use of this site in relation to the EBA transformation of social organization toward urbanism, this study explores strontium isotopic variation using laser ablation-multicollector-inductively coupled plasma-mass spectrometry (LA-MC-ICP-MS) to observe movement to and from the local area. Strontium (Sr) isotope ratios throughout the developmental periods of human enamel were used to indicate locality and patterns of mobility at WF100. Thirty-one samples consisting of a collection of permanent incisors, premolars, and first and third molars, in addition to two deciduous molars were analyzed alongside eleven local faunal samples. Initial results indicate variable patterns of mobility throughout the individual's childhood development, with some increased instances of consistent locality in later childhood. This supports arguments for a more diversified and regionally specific social organization in EBA Jordan and Wadi Faynan, that may embrace a spectrum of sedentism and transhumance in childhood. These results highlight both the potential for, and challenges of conducting further LA-MC-ICP-MS analysis of Sr in the broader Jordan landscape and provide novel insights into EBA mobility using sequential dental sampling.

Acknowledgements

Moving to a new province for this program would never have been possible without the people and generous funding bodies I have included here. The list is long, and almost certainly missing some of the individuals who have helped me along the way so to anyone who has ever encouraged me to pursue my passions, helped me through tough times, or helped give me the confidence to believe I could do this at all, you have my thanks and my apologies for not being able to include you by name here. There are not enough pages in the world to list you all.

For the immeasurable amount of support and guidance I have received throughout this program I would like to first thank my supervisor Dr. Alexis Dolphin. Without your support none of this would have been possible and you have my thanks for your endless patience with my many questions and concerns.

I also extend my gratitude to Dr Russell Adams and the Barqa Landscape Project for allowing me to study this collection through the ACEBiolab. Your expertise on archaeology in Jordan and the Wadi Faynan region has been essential to this research.

To Dr. Chris Yakymchuck and the wonderful people at the Metal Isotope Geochemistry Laboratory thank you for your patience as I learned an entirely new set of lab skills and for the wonderful conversations that brightened long days in the lab.

Dr. Russell Adams and Dr. Chris Yakymchuck you both also have my appreciation for serving on my committee and taking time out of your important work to help me ensure I have written a thesis I can be proud of and encouraging my development as a new researcher.

For their financial contributions to this research, I thank the Iris Yuzdepski foundation and the Arts Endowment fund. Your contributions to student education in this program are an essential part of encouraging researchers to explore incredible research and help remove barriers to students like myself to pursue their interests in higher education.

Of course, the faculty and staff of the Department of Waterloo have my thanks for their teaching expertise and guidance navigating this program and the formal research environment. To Dr. Adrienne Lo thank you for being so wonderful and helping me feel confident in exploring different avenues for anthropological pursuits in public outreach and education.

To the 2025 MA Public Issues Anthropology cohort thank you for your endless support through the late night paper writing, practice presentations, and your diverse anthropological insights. To each of you I also thank you for your friendship and personal support throughout this process as a newcomer to this province and university, I love you all.

To my absolute steadying forces through this experience Cassie and Aicha you have both been so wonderful and have made the many challenges of moving to a new province, school, and environment so enjoyable. Thank you for always encouraging me to be better and kinder to myself.

To my friends and family, you have my appreciation for all you do. Entering this program with a new disability has been scary and a difficult new challenge however, the support I receive every day from my parents, stepparents, grandparents, cousins, in-laws, and friends both here in Ontario as well as in Western Canada and beyond has kept me going in my journey.

To my partner Noah Brooks you are an inspiration for me every day. Your work ethic and pursuit of research excellence is a feat on its own, not to mention the sacrifices you have made to support me through a surprising number of challenges over the last 8 years. Thank you so much for being willing to move provinces with me and helping me believe in myself and my abilities as a researcher. You make me a better person, researcher, and human being in general, and I don't know what I would ever do without you. Your patience and understanding have been so essential to this process, and you and Mando (the cat) are the reasons I have the confidence to be here at all.

Table of Contents

AUTHOR'S DECLARATION ..... *II*

ABSTRACT ..... *III*

ACKNOWLEDGEMENTS ..... *IV*

LIST OF FIGURES ..... *VIII*

LIST OF TABLES ..... *X*

LIST OF ABBREVIATIONS ..... *XI*

CHAPTER 1: INTRODUCTION *1*

1.1 RESEARCH DESIGN AND SCOPE 1

1.2 THEORETICAL APPROACHES TO BIOARCHAEOLOGY: BIOCULTURAL THEORY AND EMBODIMENT 2

1.3 PUBLIC ISSUES ANTHROPOLOGY IN BIOARCHAEOLOGY 5

1.4 ETHICAL CONSIDERATIONS 7

CHAPTER 2: BACKGROUND *10*

2.1 ARCHAEOLOGY IN JORDAN 10

2.1.1 Social organization in the southern Levant *11*

2.1.3 Bioarchaeology and EBA Jordan *14*

2.2 WADI FAYNAN 15

2.2.1 Wadi Faynan 100 ..... *16*

2.2.2 Archaeology at Wadi Faynan 100 ..... *16*

2.3 STRONTIUM ISOTOPES 18

2.3.2 Strontium isotopes and the environment *19*

2.3.3 Human dentition and Sr isotopes *21*

2.4 LA-ICP-MC-MS 25

CHAPTER 3: METHODS *27*

3.1 SAMPLE SELECTION AND DIAGENESIS 27

3.1.2 Faunal Sample selection *29*

3.2 LA-ICP-MC-MS 30

3.2.1 Instrument parameters and operation *30*

3.2.2 Laser ablation line placement *32*

3.2.2 Statistical analysis *34*

3.3 INTERPRETATION PARAMETERS FOR ASSESSING LOCALITY 34

CHAPTER 4: RESULTS *36*

4.1 LOCAL BIOAVAILABLE STRONTIUM 36

4.2 LOCALITY OF SAMPLES 38

4.3 INCISORS 41

4.3.1 Non-Local *41*

4.4 PREMOLARS 45
4.4.1 Local *46*
4.4.2 Non-local *47*
4.4.2 Variably local *53*
4.5 FIRST MOLARS 54
4.5.1 Local *56*
4.5.2 Primarily non-local *60*
4.5 THIRD MOLARS 70
5.5.1 Local *71*

CHAPTER 5: DISCUSSION ***81***

5.1.1 LOCAL AND NON-LOCAL MOBILITY 81
5.2.1 SOCIAL ORGANIZATION 82
5.3.1 CHALLENGES OF USING SEQUENTIAL SR ANALYSIS IN JORDAN 89
5.4.1 CONCLUSIONS 93
5.4.2 Future directions *94*

REFERENCES ***96***

APPENDIX A: METHODOLOGICAL PRINCIPLES OF ISOTOPIC ANALYSIS 108
A.1 Mass spectrometry *108*
A.2 Ca^{2+} substitution with Sr^{2+} basic principles and equilibrium *108*
APPENDIX B: SUPPLEMENTARY MATERIALS 109
B.1 Descriptive statistics *109*
B.2 Bioavailable strontium normality tests *111*

List of Figures

Figure 1. Timeline of Early Bronze Age periods in Jordan based on radiocarbon dates for EB IA, EB IB, EBII, and EBIII (Philip, 2008).....11
Figure 2. Example of Isoscape map indicating integrated bioavailable and geological Sr stable isotope ratios throughout the southern levant. 20
Figure 3. Example of tooth with laser line 32
Figure 4. Local Bioavailable ^{87}Sr:^{86}Sr plot. 36
Figure 5. Normality plots. 38
Figure 6. Plot of mean $^{87}Sr/^{86}Sr$ by sample with 95% Confidence interval bars.. 39
Figure 7. Timeseries plot of Tooth #113 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range... 43
Figure 8. Timeseries plot of Tooth #167 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range... 44
Figure 9. Timeseries plot of Tooth #24 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. 46
Figure 10. Timeseries plot of Tooth #121 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 48
Figure 11. Timeseries plot of Tooth #033 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 49
Figure 12. Timeseries plot of Tooth #25 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 50
Figure 13. Timeseries plot of Tooth #26 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 51
Figure 14. Timeseries plot of Tooth #28 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 52
Figure 15. Timeseries plot of Tooth #29 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 54
Figure 16. Timeseries plot of Tooth #002 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. 57
Figure 17. Timeseries plot of Tooth #014 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 58
Figure 18. Timeseries plot of Tooth #031 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 59
Figure 19. Timeseries plot of Tooth #032 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 60
Figure 20. Timeseries plot of Tooth #01 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 61
Figure 21. Timeseries plot of Tooth #03 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 63
Figure 22. Timeseries plot of Tooth #02 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 64

Figure 23. Timeseries plot of Tooth #04 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 65
Figure 24. Timeseries plot of Tooth #06 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 66
Figure 25. Timeseries plot of Tooth #09 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 67
Figure 26. Timeseries plot of Tooth #08 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 68
Figure 27. Timeseries plot of Tooth #11 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 69
Figure 28. Timeseries plot of Tooth #17 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 72
Figure 29. Timeseries plot of Tooth #19 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 73
Figure 30. Timeseries plot of Tooth #22 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 74
Figure 31. Timeseries plot of Tooth #13 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 76
Figure 32. Timeseries plot of Tooth #12 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 77
Figure 33. Timeseries plot of Tooth #14 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 78
Figure 34. Timeseries plot of Tooth #15 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 79
Figure 35. Timeseries plot of Tooth #21 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.. 80
Figure 36. Comparison of all long term moving averages (Lowess) of all premolar samples with approximate ages 82
Figure 37. Comparison of all long term moving averages (Lowess) of all incisor samples with approximate ages 84
Figure 38. Comparison of all long term moving averages (Lowess) of all first molar samples with approximate ages 85
Figure 39. Comparisons of long-term moving averages (Lowess) for all Third molar samples with approximate ages. 86

List of Tables

Table 1. Tooth development initiation for human dentition (Hillson, 2024)..... 23
Table 2. List of samples used in this study. 28
Table 3. List of faunal samples and identification numbers. 29
Table 4. Instrument parameters provided by Dr. Chris Yakymchuk (2025)..... 31
Table 5. Information table for Incisor samples and results 41
Table 6. Information table for premolar samples and results 45
Table 7. Information table for first molar samples and results.. 54
Table 8. Information table for third molar samples and results..... 70

List of Abbreviations

(

(OH)
Hydroxyl group 21

8

^{86}Sr
strontium isotope (86) 19
^{87}Sr
strontium isotope (87) 19
$^{87}Sr/^{86}Sr$
Ratio of ^{87}Sr to ^{86}Sr 19

A

ACEBio lab
Ancient and Contemporary Environmental Bioindicators Laboratory 1

B

BLP
Barqa Landscape Project 1

C

Ca^{2+}
Calcium (cation) 21
CI
Confidence Interval 95% (unless otherwise noted) 33

E

EB I
Early Bronze Age I 10
EB IA
Early Bronze age IA/ Early EB I 10
EB IB
Early Bronze Age IB/Late EB I 10
EBA
Early Bronze Age 1

I

ICP-MS
Inductively Coupled Mass Spectrometry 25

L

LA-MC-ICP-MS
Laser ablation - inductively coupled - multicollector - mass spectrometry 25

P

PIA
Public Issues Anthropology 5
PO_4
Phosphate 21

R

Rb
Rubidium 20

S

Sr
strontium (atom) 2
Sr^{2+}
strontium cation 22

W

WF100
Wadi Faynan 100 1

Chapter 1: Introduction

1.1 Research design and scope

Wadi Faynan 100 (WF100), an Early Bronze Age (EBA) archaeological site, is located in the Wadi Faynan region of southern Jordan which is occupied in large part by local Bedouin populations as well as local villages (Palmer et al., 2007). The region of Wadi Faynan itself has a long history of land use evidenced by archaeological sites throughout the region ranging from neolithic/chalcolithic settlements to the Ottoman period (Barker et al., 2007; Dolphin & Adams, 2024; El-Rishi et al., 2007). In 2009 the Barqa Landscape Project (BLP) initiated research in Wadi Faynan to better understand the scale of metallurgical production in antiquity which included WF100 (Dolphin & Adams, 2024). In comparison to other EBA sites in the Levant, life at WF100 itself is still largely a mystery, and bioarchaeological studies were initiated very recently in 2019. Under the supervision of Dr. Alexis Dolphin and the Ancient and Contemporary Environmental Bioindicators Lab (ACEBiolab) this approach seeks to expand understanding about the lives and health of the people who had utilized the site. Though studies suggest that this site was possibly domestic (though not a full-scale urban site) using traditional archaeological methods such as architectural and artifact analysis, the mobility of the population has not yet been explored to clarify these interpretations, and the nature of the site's use remains unclear.

Bioarchaeological methods for research on human mobility have proven increasingly useful to investigators, particularly when they are used in conjunction with cultural evidence (Agarwal, 2016; Gregoricka, 2021; Schrader & Torres-Rouff, 2020). These studies often explore

concepts such as social organization and population interaction in ancient peoples, while providing important context for studies which depend on knowledge of mobility and biodistance, such as disease evolution and transmission (Gregoricka, 2021). One of the ways that researchers harness bioarchaeological methods is through the use of chemical analyses (Agarwal, 2016; Gregoricka, 2021; Gregoricka et al., 2020; Kramer et al., 2021; Schrader & Torres-Rouff, 2020) with the understanding that chemical integration of geographically specific elements into the skeleton can be translated to empirical data indicating physical movement across landscapes.

This study mobilizes such an approach by employing minimally destructive stable isotopic methods to explore mobility at WF100. Being situated within the biocultural paradigm, it will also explore how these chemical changes can speak to overarching social and environmental influences which initiate them. This approach provides the first study of the mobility for individuals buried at EBA WF100 by investigating whether strontium (Sr) stable isotope ratios vary over developmental time in the enamel of WF100 individuals during their childhoods. These results may further clarify other aspects of social organization and life at WF100 such as heavy metal exposure which is of interest to the principal investigators of the BLP.

1.2 Theoretical approaches to bioarchaeology: Biocultural theory and embodiment

Popularized conceptualizations of the human body after death have often defaulted to the view that the corpse is returned to being a non-social object which is entirely biological material in the absence of the human consciousness (Agarwal & Beauschesne, 2011; Cheverko et al., 2020; Moon et al., 2020). Research inquiries under this view are restricted to the hereditary,

discrete traits, and demographics such as height and pathology in addition to basic analyses such as age at death, sex, etc. A viewpoint which emphasizes discrete, categorical, and universal traits which make up the typical human body in its default functions under the assumption that cultural and environmental contexts cannot be observed in human remains (Lock & Nguyen, 2010; Moon et al., 2020; Zuckerman & Armelagos, 2011). Biocultural theory challenges this notion, recognizing the dialectical relationship between body and environment, in which neither is exclusively responsible for shaping or being shaped by the other. (Cheverko et al., 2020; Leatherman & Goodman, 2020; Zuckerman & Armelagos, 2011). The body is seen as a malleable being which is continuously adapting to the sociocultural and environmental contexts in which humans interact thus, the body can be seen at any given time as material evidence of human social and cultural environments. Given that bioarchaeology is a discipline charged with reconstructing the past based on biological evidence this inherently requires the employment of biocultural theory in any investigations (Agarwal & Glencross, 2011; Cheverko et al., 2020; Schrader & Torres-Rouff, 2020; Zuckerman et al., 2014).

Embodiment theory is rooted in social theory and has more recently been harnessed as a way of understanding biological embodiment in the lived experiences of past individuals as a way of reconstructing the past (Schrader & Torres-Rouff, 2020). While it engages with the interaction of the body and culture similarly to other biocultural theories, Schrader and Rouff (2020) argue that "Using an embodiment framework, human remains can be viewed as experiential, social, and agentive, allowing a wealth of interpretive lenses that were previously inaccessible concerning identity, intimacy, and the experience of the archaeological past" (Schrader & Torres-Rouff, 2020, 15). This approach prioritizes the experiential aspects of life, particularly with regard to the continuous interaction of cultural and biological mechanisms which results in a social body,

which defies the normative homogenization of the body as a vessel and acts as both agent and subject in its unique cultural and physical environments(Leatherman & Goodman, 2020; Lock & Nguyen, 2010; Schrader & Torres-Rouff, 2020; Tilley & Cameron-Daum, 2017; Zuckerman et al., 2014) In this sense, the body and the environment are mutually constitutive, with the cascade of biological adaptations affecting the way an individual experiences and shapes their physical and cultural environment, while these environments also shape biological adaptations. Furthermore, the process of embodiment is continuous and represents the body as a social and material subject, such that any study of the body is specifically situated within a given instance of biosocial differentiation (Lock & Nguyen, 2010)

In the case of mobility and social organization research, embodiment of both conscious and unconscious cultural/physical environments helps researchers understand aspects of identity throughout the life course of individuals (Chesson, 2001; Gregoricka, 2021; Ingman et al., 2021; Schrader & Torres-Rouff, 2020; Tilley & Cameron-Daum, 2017). This approach is limited in that it is in some ways too broad to address the overarching identity of individuals and the multiplicity of embodied contexts (Schrader & Torres-Rouff, 2020). However, using specific research questions focused on narrow biological changes through the broader lens of embodied social and physical contexts can expand the specificity and flexibility of analysis, rather than adopting a cause-and-effect approach to skeletal plasticity within the constraints of the broader body of contextual knowledge (Agarwal, 2016; Gregoricka et al., 2020). In this sense, by isolating a specific change such as isotopic signaling, we can observe changes as embodied indications of a collection of embodied contexts by asking specific questions about the way these mechanisms appear. For example, researchers can ask questions such as whether there are patterns of non-local and local seasonal movement, questions about individual or community

wide migration, and understand things such as social organization or subsistence practices. As such, this study aims to understand the mobility of these individuals as embodied aspects of social organization regarding landscape use[1]. In this sense, the isotopic ratios and their values over the development of the individual are understood to be an embodied chemical representation of a part of their life course (social organization and childhood development) through which we may observe a small portion of through this analysis.

1.3 Public Issues Anthropology in Bioarchaeology

As with any research discipline, investigators are beholden to ethical obligations to the public which we, as academics and researchers, serve. While anthropology has always had some interaction with public issues in its research design, the phrase – Public Issues Anthropology (PIA) – was only officially introduced by Robert Borofsky & Antonio De Lauri in the 1990's to define an anthropology which was beneficial to and collaborative with the 'publics' with whom we engage (Borofsky & De Lauri, 2019). In the modern sociopolitical environment of anthropology, Borofsky & De Lauri (2019) encourage researchers to practice anthropology as a transparent, consensual, collaborative, and reflexive anthropology, which extend beyond the isolated academic circle to the public stakeholders of our research such as local community members, governing bodies, and descendants; Their argument being that in the modern age of increased ability to engage publicly as intellectuals, it is our responsibility to do so as an avenue

[1] "use" here refers to the ways in which individuals are physically existing on the landscape, rather than how they are shaping it through activities such as agricultural use.

for bearing witness to past lives and social injustices and acting as an accessible academic source for the public to communicate the diversity of human experience. Despite its official introduction, these values are similarly echoed in many other anthropological works though under different names, particularly those focusing on ethical practice in anthropology(Alpaslan-Roodenberg et al., 2021; Kiddey, 2020; Mithen, Ahmed Rabbani, et al., 2025; Zuckerman et al., 2014).

Public Issues Anthropology has major implications for archaeological research as the discipline increasingly reflects on public engagement, public data availability, consultation/collaboration, and bearing witness to the individuals we study. While not always explicitly named as public anthropology, archaeological discourse on pursuing anthropological archaeology through ethical approaches echo the values presented by Borofsky and De Lauri (see Hogg et al., 2017; Stahl, 2020; Zuckerman et al., 2014). Voss (2018) notes that "archaeological evidence is never innocent of the conditions of its production. Whose pasts are investigated, what counts as evidence, how the material record is interpreted: even as archaeology breaks certain frames, it relies on and establishes others" (Voss, 2018, 309). Being grounded in social and cultural anthropological discourse, approach to anthropological research may be further mobilized in the interdisciplinary praxus of bioarchaeology. Researchers such as De León (2013) and Voss (2018) have demonstrated the applications of these principles in their own research which is highly engaged with stakeholder discourse and collaboration. Furthermore, as bioarchaeologists address the influence of colonial and antiquarian influences on early skeletal collections research collaboration and publicly beneficial research are essential for the production of meaningful knowledge (Agarwal & Glencross, 2011; Booth et al., 2020; Buikstra et al., 2022; Squires et al., 2020; Zuckerman et al., 2014).

1.4 Ethical Considerations

A fundamental source of tension within bioarchaeological research is the ethical procurement, use, and curation of human remains (Booth et al., 2020; Dolphin et al., 2016; Gregoricka et al., 2020; Moon et al., 2020; Stantis et al., 2023). Increased access to, and innovation of, scientific sampling methods in bioarchaeological research has improved the reliability, accuracy, and scope of inquiry in the field (Booth et al., 2020; Dolphin et al., 2016). However, significant ethical concerns have been raised by public stakeholders such as local communities, descendants, and bioarchaeologists themselves regarding who is allowed to determine the sampling methods, presentation of results, and the perceived perpetual rights of individuals in death such as consent to study (Alpaslan-Roodenberg et al., 2021; Booth et al., 2020; Kukutai & Black, 2024; Robbins Schug et al., 2025; Zuckerman et al., 2014). Situating this study within the values of PIA highlights the importance of establishing ethical guidelines which are relevant to local communities, and enables us to engage *meaningfully*, that is in a way which does not center only the academic perspective of what is right or worth studying, with the public in a way that is beneficial and addresses stakeholder concerns. As such, this approach emphasizes the importance of relational ethics which are relative to academic AND local community and stakeholder interpretations of what is ethically acceptable.

Economically, this study indirectly reinforces the archaeological tourism industry in Jordan by adding to the understanding of the prehistoric archaeological sites in the Wadi Faynan region.

The economy of the local community in Faynan is in part supported by the local tourism industry (Mithen et al., 2025; Palmer et al., 2007), and this research helps support ongoing archaeological tourism by supporting future research and inquiry in the area. In recognition of the diversity of pre-historic peoples in the southern Levant, this study employs a regionally novel approach which highlights the importance of intentionality of research in producing meaningful studies in a historically colonialized archaeological research context by demonstrating the harm that homogenization of these expansive landscapes can do to the academic rigour of our knowledge foundation which can affect future studies and perpetuate biases of social complexity and organization (See *2.1.1 Social organization in the southern Levant* for a more in-depth discussion of this issue in the context of the Levant).

Destructive analysis of the samples is the only option for empirically studying the mobility of these individuals chemically which, in some cases, can prove problematic (Gregoricka, 2021). In terms of the general public and local communities, destructive analysis is not a concern that was raised by the governmental bodies of Jordan, and thus far negative feedback regarding destructive analysis of the samples in the collection has not been received. However, within the bioarchaeological community the destructive analysis of samples has been scrutinized due to the all too common unnecessary destruction of human remains (Booth et al., 2020; Dolphin et al., 2016; Gregoricka, 2021; Robbins Schug et al., 2025). In these cases, the issue is often the potential future implications for stakeholders because of arbitrary or unnecessarily destructive methods due to ignorance and failure to consider the full spectrum of analytical methods. Booth et al. (2020) argues that when conducting any research on human remains regardless of the approval by governing bodies, it is essential to consider the future implications of such research with regard to the preservation and potential for repatriation of remains if requested. As such we

have given substantial consideration to the methods for sampling for this study to prevent any unnecessary destruction of remains.

Following the guidelines outlined by Dolphin et al. (2016), stable isotopic analysis was chosen specifically due to the method of sampling available given that the samples were already thin sliced and embedded in resin for destructive analysis. Where other isotopic elements require a larger quantity of material for analysis, strontium ratios can be sampled using a highly precise laser beam which destroys only a microscopic line of enamel down the length of the tooth. Furthermore, we considered what future research could be done and what research had already been completed, prioritizing the use of samples that were already prepared and screened for quality of preservation. This maximizes the amount of research that can be completed for each tooth. This study also intentionally used samples which had already been documented digitally to ensure future osteological studies could be completed if required. Most significantly, our study is highly specific and relevant to previous and publicly relevant research for the current communities in Wadi Faynan, whilst also documenting and understanding the lives of those at WF100 contributing to the broader understanding and perception of the prehistoric Levant. This study enables a portion of their lives to be understood within the context of the prehistory of Jordan for the benefit of local resident communities and the broader Jordanian tourist industry.

Chapter 2: Background

2.1 Archaeology in Jordan

In spite of a long history of archaeological study in Jordan, diverse research specialties such as anthropological archaeology and bioarchaeology have only recently begun to proliferate the research landscape (Adams, 2008; Sheridan, 2017). This transformation has helped to integrate the research in Jordan with increasingly reflexive and diverse research interests and approaches. Such transformations in theoretical and practical approaches have led to new questions about the previous conceptualizations of life in the southern Levant based on archaeological evidence (or lack thereof). This study focusses on the EBA in Jordan which has historically been broken up into four distinct periods (Figure 1): I, II, III, and IV (Philip, 2008). EB I has two identified sub-periods: EB IA and EB IB. However, some scholars argue that these two stages are too strict for the variable stages of the EB I, preferring to define the EB I as separated into an early and late stages which accommodates any other perceived substages that may not fit within the bounds of EB IA or IB. Variations in these interpretations are largely due to the result of extreme regionality of pottery throughout the EB I which results in an inconsistent timeline throughout the EB I and highlights the importance of a regional approach. The site of interest is identified as an EB IB site, and as such is the time period of interest in this

study. As the subperiod contention is outside of the scope of this study we refer to WF100 as an EB IB site and understand EB IB as homologous to the phrase: late EB I.

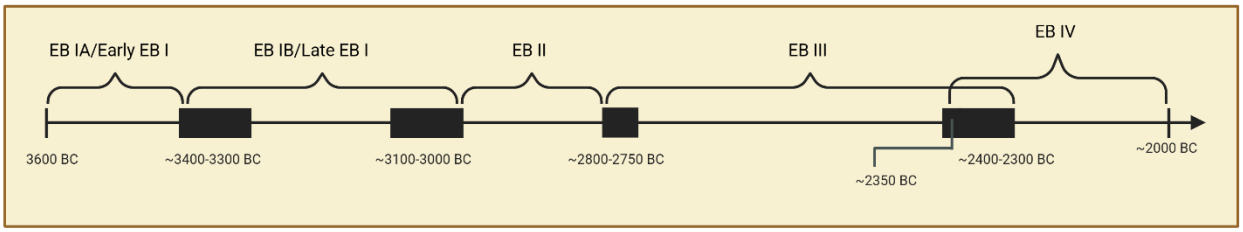


Figure 1. Timeline of Early Bronze Age periods in Jordan based on radiocarbon dates for EB IA, EB IB, EBII, and EBIII (Philip, 2008). As well as EB IV date range (Palumbo, 2008). Created in Biorender

2.1.1 Social organization in the southern Levant

One of the areas of re-consideration in Jordanian archaeology, particularly in the EB I-III, is the social organization of these which have previously been identified as urban centers (Philip, 2008). This has challenged our understandings of life in EB I-III Jordan (and the broader southern Levant), and the view that society evolved toward a city-state style occupation (Chesson & Goodale, 2014; Nicolle, 2023; Philip, 2008). This linear societal progression has identifiable developmental stages in the archaeological record, a parallel to the development of societies such as Mesopotamia and Egypt (Nicolle, 2023; Philip, 2008). Historical researchers argue that EB I settlements in Jordan also follow these predictable stages of progression toward urban city states (Chesson, 2023; Nicolle, 2023; Philip, 2008).

The city-state model of social development in Jordan equates the characteristic walled settlements found in EB I-II sites with the large urban city-state societies of Egypt and Mesopotamia in the same time period (Philip, 2008). However, contemporary researchers have critiqued this approach, citing the vastly diverse landscapes, population sizes, and sociocultural contexts present in the archaeological record (Chesson, 2023; Nicolle, 2023; Philip, 2008). The presence of walled settlements, typically interpreted as defensive or large structured walls, are characteristic of the EBA landscape in Jordan and are often considered an indication of sedentarism and social complexity as they are thought to correlate with the centralization of power and administrative hierarchies (Philip, 2008). Smaller population sizes at these sites in Jordan as well as conflicting artifact evidence of a particular stage of development are incongruous with this argument. Based on evidence of ongoing communication and interaction across the landscape combined with evidence of small populations and transient occupation of these sites, Philip (2008) suggests that "interludes of occupation at many walled sites appear to have been relatively short, or punctuated, suggesting that these did not represent the core structuring elements as part of a wider landscape – " (Philip, 2008, p. 210). Other authors such as Chesson, 2023; Honeychurch & Makarewicz, 2016; Nicolle, 2023a further develop these sentiments to include the concepts of choice and the flexibility of movement in these unique communities, and the way they shape and are shaped by social organization and associated roles. Nicolle (2023) argues that the transient use of occupation sites potentially dependent on seasonality and environmental influences demonstrates that the increased development in agriculture can exist *with* different types of social organization that do not adhere to the move toward sedentarism which traditional perspectives argue for. This has been supported by a variety of archaeological data, particularly at EB I sites (Philip, 2008) and the disconnect

between the expected and actual use of sites and pottery have continue to undermine these assumptions due to conflicting categorical data (Nicolle, 2023; Philip, 2008).

The suggestion that the homogenization of these sites and their singular purpose of urban development on the landscape continue to be challenged within Jordan and in other early civilizations, which problematize the one size fits all model of linear progression to social complexity (Cavazzuti et al., 2019; Chesson, 2001, 2023; Chesson & Goodale, 2014; Honeychurch & Makarewicz, 2016; Nicolle, 2023; Philip, 2008). New insights suggest that a regional or sub-regional analysis with comparison to the broader region is a more appropriate approach that reflects unique ways in which societies become more complex in response to different environments and cultural influences (Chesson, 2023; Nicolle, 2023). Modern archaeologists in Jordan harness new methods and theory to better understand the diversity of social complexity particularly regarding the level of mobility and sedentarism at these sites (Nicolle, 2023; Philip, 2008). Understanding how individuals utilize these sites in response to their unique environments is essential to highlighting more diverse indications of increasing social complexity. The clarification provided by understanding mobility not only indicates whether or not individuals were sedentary, but also how their unique use of other archaeological evidence may provide a larger window into the less acknowledged ways in which societies may become more complex including societies which do not develop into strictly hierarchical organizations

2.1.3 Bioarchaeology and EBA Jordan

Rethinking social organization and the checklist of requirements for each stage of social evolution to 'urban'[2] society has proven to be somewhat controversial (Philip, 2008). To clarify the discourse between past and current perspectives, recent studies have harnessed modern archaeological methods, including bioarchaeology, to present new perspectives on these issues which embrace a biocultural and evidence first approach (see studies such as Chesson, 2023; Dolphin & Adams, 2024; Gregoricka et al., 2020). Arguably one of the most well researched EBA sites in Jordan, Bab edh Dhra has been the subject of many bioarchaeological studies encompassing many of the research areas discussed above. Studies directly related to Bab edh Dhra (see Chesson, 2001, 2023; Chesson & Goodale, 2014; Gregoricka et al., 2020; Ortner & Frohlich, 2007) are essential to refer to as a result of its prominence in the bioarchaeological literature for the region and continued research on the EBA in Jordan. Many of these authors have helped to advance the previously discussed argument for a more nuanced interpretation of archaeological evidence of social complexity and lifeways (Chesson, 2001, 2023; Chesson & Goodale, 2014; Gregoricka et al., 2020; Sheridan, 2017). Most recently, Chesson (2023) used mortuary archaeology to compare both cultural and bioarchaeological differences between Bab edh Dhra and associated sites through the lens of unique regional processes of interaction with other communities. While the richness of bioarchaeological research at Bab edh Dhra is certainly helpful in understanding life in EBA Jordan, to apply the knowledge gained from this site to the

[2] Urbanism here is understood stratified, and densely populated communities in contrast with smaller villages which rely on the urban communities for resources, governing, etc (Philip, 2008). This reflects the traditional definitions of urbanism in Jordanian archaeology which links urbanism with social complexity.

entirety of the Jordan region and the Southern Levant without exception is to perpetuate the homogenization of these communities. As such, exploring other regions and sites using bioarchaeological techniques is important for understanding the broader landscape and its associated social diversity so as not to fall prey to sampling bias and universalist approaches. Furthermore, employing sub-regional analysis in site investigations promotes an integrated approach to understanding the nuances of individual occupations and is especially relevant to the EB I given the highly regionalized aspects of these communities (Philip, 2008).

2.2 Wadi Faynan

Wadi Faynan 100 is located in the Wadi Faynan region of southern Jordan, which is occupied by the local Bedouin population as well as a small village presence (Palmer et al., 2007)). Today, this region is characterized by desertification and a rocky landscape, however, in the EBA it was more likely to have experienced periods of flooding and would have generally been a more moist climate. Archaeological interest in the region goes back as far as 1988 and is one of the earliest examples of extensive metallurgical production. In 2009, the Barqa Landscape Project initiated research in Wadi Faynan to better understand the scale of metallurgical production in antiquity in relation to their environmental impact, focusing on archaeological and metallurgical production sites. The EBA IB investigation of Wadi Faynan 100 and subsequently the initial stages of the research presented here began in 2019 (Dolphin & Adams, 2024). Today much of the landscape, including areas with archaeological sites, are still used by the local communities for agricultural purposes, which threaten site integrity (Dolphin & Adams, 2024; Palmer et al., 2007). The archaeological landscape of Wadi Faynan is one such example of a

region which goes against the suggestion of societal progression toward a hierarchical society. The region shows clear evidence of complex and specialized roles for mining, smelting, and production alongside an absence of the other 'requirements' for association with a stage on the linear timeline toward urbanism.

2.2.1 Wadi Faynan 100

Researchers studying Wadi Faynan 100, an EB IB site located in the Wadi Faynan region of Jordan, have recently begun integrating bioarchaeological methods of investigating the social and cultural lives of those buried there (Dolphin & Adams, 2024). While the investigation of this site in the timeline of archaeology in Jordan is relatively recent, the rapidly changing theoretical landscape for social organization research in Jordan (Philip, 2008) has presented the opportunity to explore aspects of social organization at the site through a new bioarchaeological lens. Recent methodological approaches to understanding social organization have placed an emphasis on the act and experience of mobility throughout the landscape as an indication of social organization and subsistence (Chesson, 2023; Nicolle, 2023; Philip, 2008). As opposed to traditional interpretations of social organization, these approaches prioritize the unique interactions between mobility, social organization, the environment, and culture regionally and sub-regionally, thereby reducing the risk of homogenization of social dynamics of the past.

2.2.2 Archaeology at Wadi Faynan 100

In comparison to other well-known sites in Jordan, such as Bab edh Dhra, which has undergone significant bioarchaeological and archaeological studies (Chesson, 2001, 2023; Gregoricka et al., 2020; Ortner & Frohlich, 2007), life at Wadi Faynan 100 is still largely a mystery. Located in the Wadi Faynan region of central Jordan, modern excavations have primarily focused on researching metallurgical use and copper production in the Faynan region, though it has been the subject of archaeological research since 1989 (Dolphin & Adams, 2024; Wright et al 1998). Wright, et al. (1998) was the first to characterize the site in the initial survey of architectural structures and artifacts, initial results indicated that WF100 is an EB 1B (possibly) domestic occupation, which they state consists of architectural elements such as possible stone walls, defensive structures, and a large cemetery situated in a desertified valley (Wright et al., 1998) though recent work at the site challenges these conclusions (Dolphin & Adams, 2024). The most recent excavations in 2019 and 2023 have marked the beginning of bioarchaeological investigations at the site, with the goal of better understanding the impact of metallurgical activities on the sites occupants and clarify the social organization and general aspects of life at WF100. With regard to social organization and the city-state model, initial archaeological investigations (Wright et al., 1998) seem to differ from modern assessments of WF100. While Barker et al. 2007 suggests that WF100 was possibly a fairly dense population with specialized roles and some forms of agricultural storage, particularly because it is the largest EBA settlement in the region (Barker et al., 2007), these are not conclusive evidence for a clear progression towards a defensive urban site (Philip, 2008) as suggested by Wright et al. 1998.

The arguments made by the most recent critiques discussed above in *Chapter 2.1.1 Social organization in the southern Levant* regarding the inconsistencies with this homogenizing and categorical model suggest that re-evaluation of these conclusions using evidence from other

research avenues would clarify the nature of this site's occupation. While the walled structures may indeed have been an indication of collective defensive or community based infrastructure which indicate some kind of hierarchy (Barker et al., 2007), Nicolle's (2022) argument that the lack of other evidence such as writing and administrative structures highlights the uncertainty of this perspective. Chesson's (2023) discussion of regionalism and mortuary difference in the settlements near Bab edh Dhra also bring up questions about the nuances of this site. They emphasize that differences between archaeological sites may not be as simple as different stages of development but that they may be regionally specific due to environmental, social, and cultural differences between sites. While it is certainly arguable that the evidence from material culture at WF100 is suggestive of domestic semi-nomadic occupation, inconclusive results of architectural analysis and evidence of trade outside of the region highlight possible areas of inaccuracy.

2.3 Strontium isotopes

While mobility can be understood through a variety of indicators such as diet and physical change, whether cultural or genetic, mobility across a landscape can also be investigated using geologically specific isotopic ratios that have been integrated into human teeth. In this study, Sr isotopic ratios are used as a measure of physical movement across the landscape when there is sufficient isotopic variability in the local landscape and sustenance sources.

2.3.2 Strontium isotopes and the environment

Elemental isotopes refer to the forms of an atom which, while maintaining the same number of protons and charge that define its molecular species, vary in their neutron count (Ellam & Ellam, 2016). The resulting forms are defined by their atomic mass and are each different isotopes of the same element. Sr for example has four isotopes, of which two are mainly relied upon in isotopic studies of mobility (Al-Shorman et al., 2025; Boethius et al., 2022; Gregoricka, 2021; Holt et al., 2021a; Neff, 2012). Both ^{87}Sr and ^{86}Sr are stable isotopes, and are not subject to radioactive decay over time (Holt et al., 2021a; Rossi et al., 2024). However, ^{87}Sr accumulates in bedrock over time as a product of the radioactive decay of Rubidium, specifically ^{87}Rb. By identifying the ratio of $^{87}Sr/^{86}Sr$, it is possible for researchers to then associate these values with geological regions due to their unique combination of natural bedrock $^{87}Sr/^{86}Sr$ ratios. The maps of regional isotopic ratio distributions across a landscape are referred to as *isoscapes.*

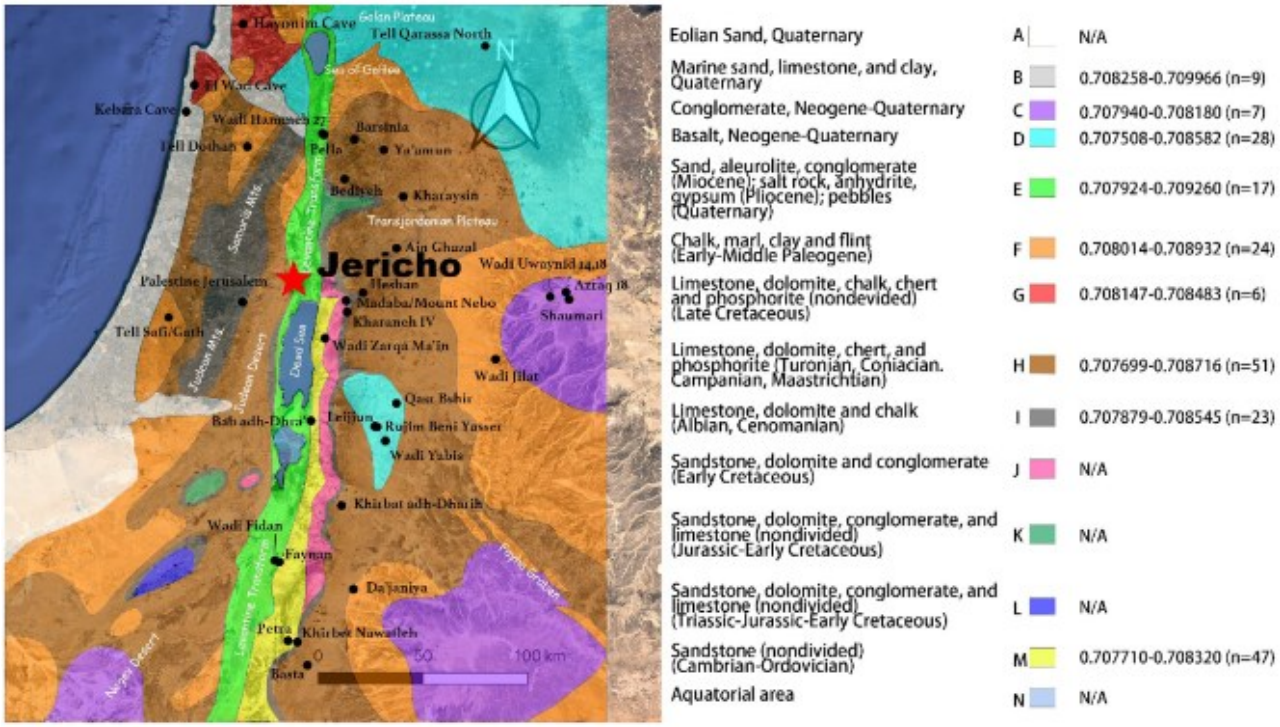


Figure 2. Example of Isoscape map indicating integrated bioavailable and geological Sr stable isotope ratios throughout the southern levant. Wadi Faynan is on the border of zones E and M. (Wang et al., 2023, page 4)

The accumulation of radiogenic Sr (^{87}Sr) in the rocks and sediments of the landscape is an extremely slow process due to the radioactive decay rate of Rubidium (Rb) which has a half-life of 48.8 million years (Holt et al., 2021a). As such, the abundance of ^{87}Sr is geologically unchanged within the timescale in which archaeological inquiry occurs, and therefore we can assume that modern geological samples represent the same geological abundance of ^{87}Sr from antiquity. Isotopic *fractionation* on the other hand is the change in abundance of each isotope in the process of transfer from source to recipient and in the geochemical process of the hydro and atmospheric cycles (Boethius et al., 2022; Flockhart et al., 2015; Holt et al., 2021a; Rossi et al., 2024). Unlike light stable isotopes such as hydrogen and carbon, Sr is less prone to fractionation in the process of uptake by plants and animal s which humans then consume (Flockhart et al., 2015) making isoscape reliability perceivably high when based off of geological values.

However, recent discourse highlights the importance of obtaining bioavailable strontium controls due to homogenization in the bioavailable environment which causes geological values to differ from human and faunal values. Different sources of Sr combine and are differentially distributed through different plant and animal systems which create a unique range of Sr ratios of any given region, and one that is dependent on the specific collection of ecosystem interactions as opposed to the baseline geological or water ratios of the region (Flockhart et al., 2015; Holt et al., 2021; Rossi et al., 2024; Wu et al., 2024). Ideally, these should be sampled over a wide area in an organized grid with a mix of both food and water sources as well as faunal remains known to be local to the sampling area, in addition to other geological sources of Sr. That being said, bioavailable sources and the extent of homogenization may make samples of water and geological values less important than those of local flora and fauna as they represent the cumulative effect of all of these influences and can be associated with a particular time period.

2.3.3 Human dentition and Sr isotopes

Human dentition is composed of three main biological tissues: enamel, dentine, and cementum, with dentine encasing the tooths roots (nerves, cementum, etc.) (Hillson, 2024). Enamel, which forms the tooth crown, develops at a known rate over time through the deposition of sequential layers of mineralized tissue at a fairly steady rate. This mineralized tissue is composed mostly of hydroxyapatite - $Ca_{10}(PO_4)_6(OH)_2$, a crystal lattice structure composed of calcium, phosphate, and hydroxyl groups, in which Ca^{2+} ions are readily substituted for

comparable ions[3] during development (Brès et al., 2021; Hillson, 2014). The organic component of enamel makes up only 4% of the entire composition, while dentine and cementum are significantly less mineralized, containing more organic components essential for preserving dental health during life (Brès et al., 2021; Hillson, 2014; Nakano et al., 2021).

This process of enamel growth and mineralization is known as amelogenesis, wherein ameloblasts derived from the dental epithelium begin enamel matrix secretion at the occlusal end of the dentine enamel junction outward toward what will become the tooths' surface, followed by mineralization of the matrix in the same pattern (Brès et al., 2021; Hillson, 2024; Li et al., 2021).. The matrix is composed of about 30% protein (amelogenin, ameloblastin, and enamelin), 30% mineral, and 30% water, and is deposited by thin rods. Calcium ribbon filaments in addition to the enamel matrix form the initial structure from which mineralization occurs. During the initiation of the maturation stage ameloblast activity begins to change, in which ameloblasts are now acting to remove the organic matrix while minerals for the final chemical structure of enamel are transported into the space. These minerals combined with the initial structure provided by the secretion stage allow the initial structure to crystallize and mature into its final structure. Mineralization of dental enamel follows a predictable and fairly reliable pattern of growth with the replacement of initial rods with crystallite rods developing at a known rate of ~ 4-6μm per day (Hillson, 2024). Once formed, enamel does not remodel[4], and thus any molecules integrated into the crystal lattice structure during enamel maturation should not change over

[3] For a more detailed description of the chemical Ca^{2+} and Sr^{2+} integration into enamel during the mineralization process as well as a note on basic equilibrium reactions please see: *A.2 Ca2+ substitution with Sr2+ basic principles and equilibrium*

[4] There is some remineralization which occurs on the surface of the enamel after mineralization however, enamel lacks collagen and therefore does not remineralize in any areas other than the exposed crown surface (Manton et al., 2025)

time, except in situations where significant alteration has occurred, such as in the case of post-mortem damage.

Table 1. Tooth development initiation for human dentition (Hillson, 2024)

Deciduous incisors	**Deciduous canines**	**Deciduous first molars**	**Deciduous second molars**
~14 weeks in utero	~ 19 weeks in utero	~ 15 weeks in utero	~ 17 weeks in utero

Incisors	**Canines**	**Premolars**	**First molars**	**Second Molars**	**Third molars**
~ 3-5 months	~ 9-10 months	~ 1.8 years	~ 30 weeks in utero	~ 3 years	~ 8 years

The predictable timing of enamel growth (Table 1) allows researchers to cross reference enamel growth during the known development period of the tooth by measuring the distance from the cusp apex to the area of interest (Hillson, 2024). For example, a first molar represents a development period starting at ~30 weeks in utero, so by measuring from the apex of the tooth where matrix deposition would start perpendicular to the rods you can turn the measurement into a function of time to understand the approximate time during development in which the area of interest occurs in. That said, the timing of these patterns are not exact, particularly when you are looking to track mineralization, and a complex interaction of temporal, environmental, hormonal, and genetic factors can affect the maturation of the enamel matrix throughout development (Li et al., 2021).

Bioarchaeologists take advantage of the natural cycle of Sr (see *2.3.2 Strontium isotopes and the environment*) and the unique mineralization process of enamel by analyzing the abundance[5] of ^{87}Sr:^{86}Sr using mass spectrometry (Boethius et al., 2022; Kramer et al., 2021). Sr is incorporated into the mineral structure of enamel and represents the bioavailable Sr available to it from sustenance sources, meaning that the Sr ratio is a result of environmental homogenization of Sr from different sources prior to ingestion and therefore is unique temporally and geographically from the original geological Sr source (Boethius et al., 2022; Flockhart et al., 2015; Holt et al., 2021).

As enamel develops, Sr isotope ratios associated with ingested food and water are incorporated into the mineralized structures of the enamel and can still be traced long after they are ingested (Boethius et al., 2022; Coffin et al., 2022 Hillson, 2024). Since enamel does not remodel as other dental tissues do, it is possible to chronologically measure Sr ratios throughout the time period of growth of the enamel, and the continuous technical innovation in the bioarchaeological field now allows for strategic sequential sampling (Boethius et al., 2022; Coffin et al., 2022; Gregoricka, 2021; Hillson, 2014; Meijer, 2018). These methods have also resulted in a diminished need for substantial amounts of the tooth to be destroyed in the sampling process, as is the norm for methods with require powdered or liquid samples of the tooth.

Currently no documentation which refers to sociocultural or physical borders which delineate the local or regional borders of WF100 has been identified, and no significant isoscape maps have been produced for the Wadi Faynan region. As such, it is not currently possible to determine the overall range of mobility or specific locations from which individuals may have

[5] "Isotopic abundance: XAE = nAE /nE, where nAE and nE are the number of atoms of the isotope AE of the element E and the total atoms of the element E in the material of interest, respectively; for example, n86Sr and nSr." Rossi, et al (2024)

visited or migrated. As such, all mobility is defined as movement into or out of the local area of WF100 and any associated patterns of these instances. Mobility is here defined as both short- and long-term movement, though other authors may choose to categorically distinguish 'types' of movement dependent on time, distance, and social circumstances (Gregoricka, 2021). This requires a control range of local and ideally also non-local bioavailable values for the surrounding regions for comparison with the data of the samples (Hillson, 2024; Boethius et al., 2022; Coffin et al., 2022; Gregoricka, 2021).

2.4 LA-ICP-MC-MS

Archaeological studies of Sr isotope ratios began utilizing inductively coupled plasma mass spectrometry (ICP-MS) in the 1960s, due to the efficiency of ion separation in digested (i.e., dissolved in acid) samples using very high temperature plasma (Neff, 2012). Owing to technological advancements, the introduction of Laser Ablation Multi-collector Inductively Coupled Plasma Mass Spectrometry (LA-MC-ICP-MS) as an alternative use of the application of ICP-MS have allowed for sampling with spatial context and diverse ion analysis while also greatly reducing the extent of sample destruction in its preparation stages. Laser ablation, where a laser is used to sample whole or micro sliced samples rather than liquified, is an on-line sampling method which has increased the target specificity to the micron level, and has significantly reduced the destruction of irreplaceable archaeological materials (Neff, 2012; Wieser et al., 2012). The specificity and preciseness of ion identification has also been greatly improved with the addition of multicollector instruments which allow for the simultaneous measurement of multiple masses, a necessity for high-precision analysis of isotopic ratios in

certain elements such as Sr., due to the small differences in mass between Sr isotopes, as well as the need to run similar molecules such as Rb to assess contamination; this technology is essential to assessing mobility over time.

Chapter 3: Methods

3.1 Sample selection and Diagenesis

Post-mortem preservation of skeletal remains is variable, and contamination in skeletal chemical indicators of embodied aspects of individual lives can skew data and generally produce poor results resulting in unnecessarily skeletal destruction (Szostek et al., 2011). The degree of diagenic alteration can be affected variably based upon the composition of bone, the type of chemical you are studying, and the effect of the burial environment. In general, the chemical changes which affect the skeleton in the postmortem burial environment can artificially inflate/obscure elemental abundance measurements. Sample degradation and contamination is a concern in Strontium Isotope analysis using dental enamel, however, in comparison to other tissues such as bone, enamel is significantly less susceptible to diagenic alteration (Budd et al., 2000; Holt et al., 2021a). For this study, diagenesis assessments relied upon the assessments performed by the authors of the studies from which they originate. Tan (2021) assessed diagenesis by assessing Ca/P ratio against a standard range of 1.8-2.7 (Szostek et al., 2011; Kohn et al., 1999). Of the samples that yielded appropriate ratios to assume a minimal likelihood of post-mortem contamination of the samples, those chosen for this study based on this, and their structural integrity are identified in Table 2. Three samples which were identified as being diagenically altered but for which trace element data had still been obtained were included in this study as comparative references for data cleaning of diagenic alteration/instrumental interference, however these were excluded from further analysis and are highlighted in (Table 2). In Ruddell (2025) diagenic alteration was assessed by analysing the fluctuations in both non-biogenically derived elements Uranium and the Lanthanum` in addition to identifying changes

occurring between Copper, Manganese and Lead with Uranium and Lanthanum. The samples identified based on Ruddell's (2025) study and surface assessment of the integrity of the thin sliced dentition – already set in resin for assessment in the case of both studies – can be found in Table 2.

Table 2. List of samples used in this study. From left to right columns identify: Identification number for each tooth from the original study, standardized Identification numbers modified for this study, tooth orientation and type standardized formula (Hillson, 2023), original study.**denotes diagenically altered sample

Tooth ID	Modified ID	Type	Original study
19.2.1.002	002	L?M1	Tan, 2021
19.3.2.091**	091	URI2	Tan, 2021
19.3.3.113	113	I	Tan, 2021
19.3.1.116**	116	URi2	Tan, 2021
19.3.3.121	121	m	Tan, 2021
19.3.99.167	167	URI2	Tan, 2021
19.5.032	032	URM1	Tan, 2021
19.5.4.014	014	M	Tan, 2021
19.5.4.028**	028	URM1	Tan, 2021
19.5.4.031	031	URM1	Tan, 2021
19.5.4.033	033	URm2	Tan, 2021
M101	01	LLM1	Ruddell, 2025
M102	02	LLM1	Ruddell, 2025
M103	03	ULM1	Ruddell, 2025
M104	04	ULM1	Ruddell, 2025
M106	06	URM1	Ruddell, 2025
M108	08	LRM1	Ruddell, 2025
M109	09	LLM1	Ruddell, 2025
M111	11	URM1	Ruddell, 2025
M301	12	ULM3	Ruddell, 2025
M302	13	ULM3	Ruddell, 2025
M303	14	ULM3	Ruddell, 2025
M304	15	ULM3	Ruddell, 2025
M306	17	ULM3	Ruddell, 2025
M308	19	LLM3	Ruddell, 2025
M310	21	URM3	Ruddell, 2025
M311	22	URM3	Ruddell, 2025
M312	23	ULM3	Ruddell, 2025

PM01	24	LLP3	Ruddell, 2025
PM02	25	LLP3	Ruddell, 2025
PM03	26	LLP4	Ruddell, 2025
PM05	28	URP3	Ruddell, 2025
PM06	29	ULP3	Ruddell, 2025

3.1.2 Faunal Sample selection

Faunal samples used in this study (**Table 3Table *3***) were found in association with the cemetery/burials themselves or on the surface of the Wadi Faynan landscape. Samples were chosen based on availability and at least one sample per grave was included to be representative of the specific graves represented in the human samples. Similar to the practices and recommendations from other studies (Holt et al., 2021; Perry et al., 2009; Price et al., 2002), the bioavailability samples consisted both of very sedentary faunal organisms (shells, likely snail) as well as small and large mammals (rodent and goat teeth) to encompass a general range of the local region.

Table 3. List of faunal samples and identification numbers. Unless otherwise identified as Shell or Goat all teeth samples are of rodent dentition.

SAMPLE	TYPE	GRAVE	YEAR OF EXCAVATION
FSHELL07	Shell	Grave 6	2023
FSHELL08	Shell	Grave 3	2019
FSHELL09	Shell	Grave 3	2019
FTOOTH01	Rodent incisor	Grave 6	2023
FTOOTH02_2	Rodent incisor	Grave 3	2019
FTOOTH05	Rodent incisor	Grave 6	2023
FTOOTH06	Rodent incisor	Grave 3	2019
FTOOTH30_GOAT	Goat incisor	Grave	

FTOOTH12	Goat molar	Field retrieval	2019
FTOOTH3	Rodent incisor	Grave 5	2019
FTOOTH4	Rodent molar	Grave 5	2019

3.2 LA-ICP-MC-MS

LA-ICP-MC-MS was conducted under the supervision of Dr. Chris Yakymchuk who also provided the below instrument parameters and procedure descriptions provided in section 3.2.1.

3.2.1 Instrument parameters and operation

Samples were analyzed using an Analyte G2 Excimer laser ablation system coupled to a Nu Plasma III multi-collector inductively coupled plasma mass spectrometer at the Metal Isotope Geochemistry Laboratory, University of Waterloo. Ablation was performed using a laser scan speed of 10 μm s^{-1}, a frequency of 20 Hz, and a fluence of 4 J/cm^2 (measured at sample surface), with a circular spot diameter of 110 μm. Ablated material was removed from the laser sample chamber using He as a carrier gas (~ 0.38 L min^{-1}). Nitrogen (~ 3 ml min^{-1}) was introduced into the aerosol via a mixing bulb before the addition of argon gas (~0.66 L min^{-1}) through a Y-junction. Specific instrument operating parameters are shown in Table 1. Standard–sample bracketing with reference materials was analyzed every ~30 minutes.

Three reference materials were analyzed. USGS-MACS3 was used as a primary reference material to correct for instrumental mass fractionation and has a $^{87}Sr/^{86}Sr$ value 0.7075532 ±

0.000002 (Jochum et al., 2011). Two secondary reference materials were used. NanoSr is a pressed pellet with a $^{87}Sr/^{86}Sr$ value 0.70757 ± 0.00004 (Weber et al., 2020). NIST 1486 (bone meal powder) was mixed ~80/20 (by weight) with Hoechst wax micropowder (Supelco; 109041) and pressed together in a uniaxial press; it has reported $^{87}Sr/^{86}Sr$ values varying from 0.709269 to 0.70964 (GeoReM; July 24 2025). The NIST 1486 reference material was used as a secondary reference material for all analytical sessions. Data were reduced using the Iolite (v3.6) software package (Patton et al., 2011) and using the Sr Isotopes (CaAr) standard data reduction scheme.

NanoSr (n = 6) reference material yielded a $^{87}Sr/^{86}Sr$ value of 0.70763 ± 0.00025 (2SE), which is within uncertainty of the accepted value. Analysis of the NIST 1486 (n = 14) pressed pellet yielded an $^{87}Sr/^{86}Sr$ value of 0.70913 ± 0.00046 (2SE), which is slightly lower than reported values from GeoReM, but within uncertainty of values from dissolution MC-ICP-MS (0.70931 ± 0.00014, 2SD; Galler et al., 2007).

Table 4. Instrument parameters provided by Dr. Chris Yakymchuk (2025)

Nu Plasma III MC-ICP-MS	
Carrier gas and flow rate	0.18 L min^{-1} (He-MFC1) + 0.20 L min^{-1} (He-MFC2) + 3 mL min^{-1} (N_2-MFC3) + 0.66 L min^{-1} (Ar). Nitrogen is added after the ablation chamber with a mixing bulb. Ar is added subsequently using a 'Y'-junction before the torch.
Auxillary gas flow rate	0.95 L min^{-1} (Ar)
Coolant gas flow rate	17 L min^{-1} (Ar)
RF power	1300 W
Reflected power	<1 W
Sample cone	Nickel (0.9 mm Orifice)
Skimmer cone	Nickel (0.6 mm Orifice)
Collector types	7 Faraday cups
Integration times	0.2 s
Masses (cup)	88 (H8), 87 (H6), 86 (H4), 85 (H2), 84 (Ax), 83 (L2), 82 (L4) amu
Ref. Materials	NanoSr ($^{87}Sr/^{86}Sr$ = 0.70757 ± 0.00004; Weber et al., 2020; ~495 µg/g Sr) NIST 1486 ($^{87}Sr/^{86}Sr$ = 0.70931 + 0.00014; Galler et al., 2007; ~264 µg/g Sr)

	USGS-MACS3 ($^{87}Sr/^{86}Sr$ = 0.7075532 ± 0.000002; Jochum et al., 2011; ~6590 µg/g Sr)
Photon Machines 193nm ArF excimer laser	
Cell	Two volume Helex cell
Sample transport tubing	1 m length (to NP2), 1.5 m length (to Agilent), PTFE 2 mm x 4 mm
MFC 1	0.18 L min^{-1} (He)
MFC 2	0.20 L min^{-1} (He)
MFC 3	3 mL min^{-1} (N_2)
Washout time	<1 s
Wavelength	193 nm ArF
Fluence	4 J cm^{-2}
Spot size	110 µm diameter circle
Scan speed	10 µm s^{-1}
Repetition rate	20 Hz

3.2.2 Laser ablation line placement

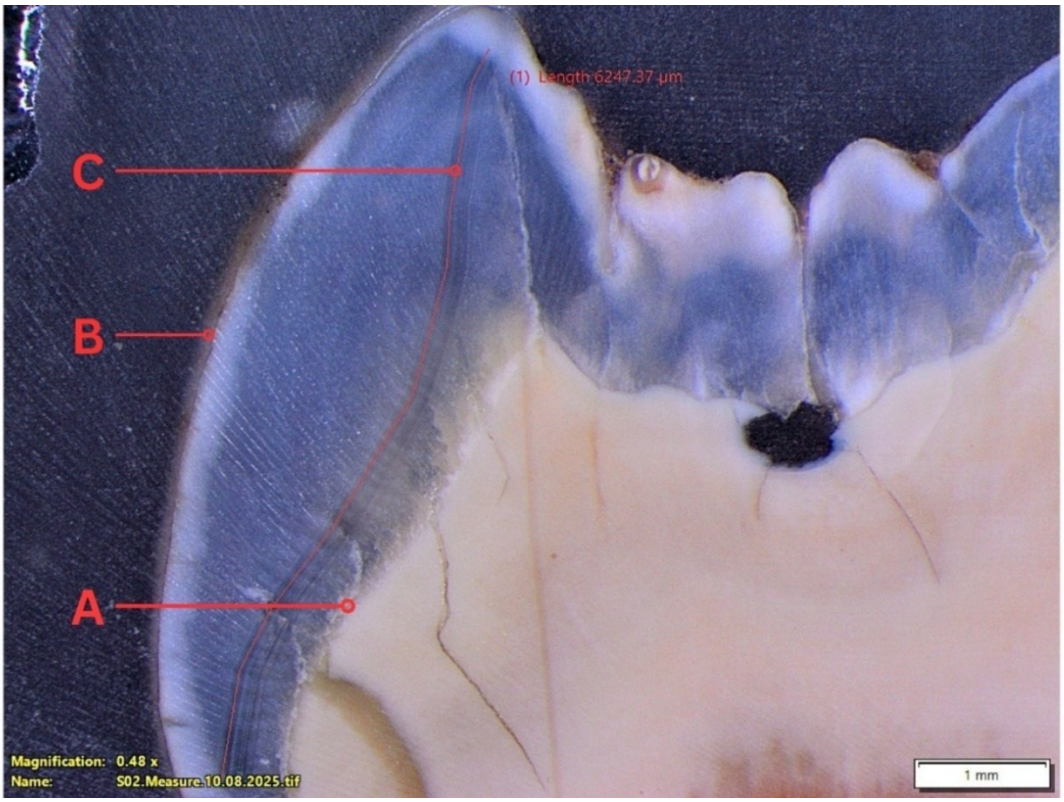


Figure *3*. Example of tooth with laser line A: DEJ. B Outer surface of the enamel. C: highlighted laser line running from tip of cusp inferiorly to the tooth cervix. Tooth is oriented such that the occlusal surface is superior to the DEJ .

In an effort to ensure that data from this study could in the future be compared to the results of previous trace element studies, any new laser lines were placed as close to the previous studies laser line as possible, ideally directly beside it. This also permitted the usage of previous diagenic alteration screening to be used as a guide for this study to mitigate the risks of contamination. Lines were placed such that they were between the enamel surface and the original line so that it would not be likely to pick up data from the dentine, but still as close as to the DEJ as possible to ensure as accurate developmental spatiotemporal analysis as possible[6]. The track lines (see Figure *3*) were run from the tip of the cusp to the end of the enamel at the tooth cervix without extending into the DEJ where possible, in cases where visibility was poor lines were sometimes run from cervix to cusp tip unknowingly. Comparison to the laser placement along the axis with the images of the teeth oriented in the tray was completed to correct for any such errors. Following ablation, all track lines were imaged using the Olympus SZX16 Stereo Microscope.

Faunal samples were ablated in a single spot on the area of interest, either on the enamel of the rodent and goats' teeth or on an unobstructed portion of shell, according to the sample type. The mean of these compiled sample ratios was calculated and the 95% Confidence interval (CI) was used to establish the local range to maintain consistency with previous published studies of locality in the Wadi Faynan region in later archaeological periods (Perry et al., 2009, 2017. Faunal tooth 30 (Goat) was run with a separate sequential line due to previous lead sequential analysis in Ruddell (2025). In order to ensure that this sample could be comparable to

[6] As noted in 2.3.3 Human dentition and Sr isotopes, mineralization rates may vary by individual. By placing the line as close to the DEJ as possible it allows the laser to sample as perpendicular to the rods as possible, while also sampling the earliest possible maturation stage whereas sampling further from the DEJ may vary because of the complex processes involved with progressively mineralizing the rod.

the other faunal values to establish a mean and CI, the mean of Faunal Tooth 20 (Goat) was calculated along with standard deviation. The mean of this sample therefore represented the bulk sampling value of Faunal Tooth 30 (goat) to allow for it to be included with the entire faunal sample population in the calculations for the local bioavailable range. All samples were also documented before and after ablation using the Olympus (model).

3.2.2 Statistical analysis

Statistical tests and plots provided were generated using Graphpad Prism Version 10.6.1 (892) for Windows, and Microsoft® Excel® for Microsoft 365 MSO (Version 2509 Build 16.0.19231.20138). 64-bit was used to compile and organize data for processing in prism. Statistical consulting was provided by Kyu Min Shim in the department of Statistics through the services of StatsConsulting (SAS) at the University of Waterloo.

3.3 Interpretation parameters for assessing locality

In the interest of being able to assess the locality of individuals, it is necessary to define to whom the local range applies, and what it *means* (empirically) to be a local. However, the consensus on how to approach this dilemma is complicated as it requires researchers to speculate on how individuals saw themselves and how others saw their communities (Tilley & Cameron-Daum, 2017), and how these perspectives can be interpreted in the chemical data (Gregoricka et al., 2020. For example, while the Sr isotope ratios represented in a bioavailable range may be

indicative of perhaps where small animals travelled to and from in the community, the perception of what is local to the individuals themselves could certainly range outside of those boundaries. For the purposes of this study we refer to locality geographically, based upon animals with a relatively small range of movement such as rodents and snails that were found associated with the burial environments as well as larger mammals associated with domestic animal management in recognition of the semi-nomadic history of the region and suggested for nearby sites such as Bab edh Dhra (Chesson, 2023). Ultimately, this approach is limited and is discussed at a more significant length in Chapter 5. For practical purposes, locality is understood chemically for the purposes of evaluating the quantitative data, with the understanding that this is at most a hypothesis on the bounds for the perceived local area, rather than a known variable.

Chapter 4: Results

4.1 Local bioavailable strontium

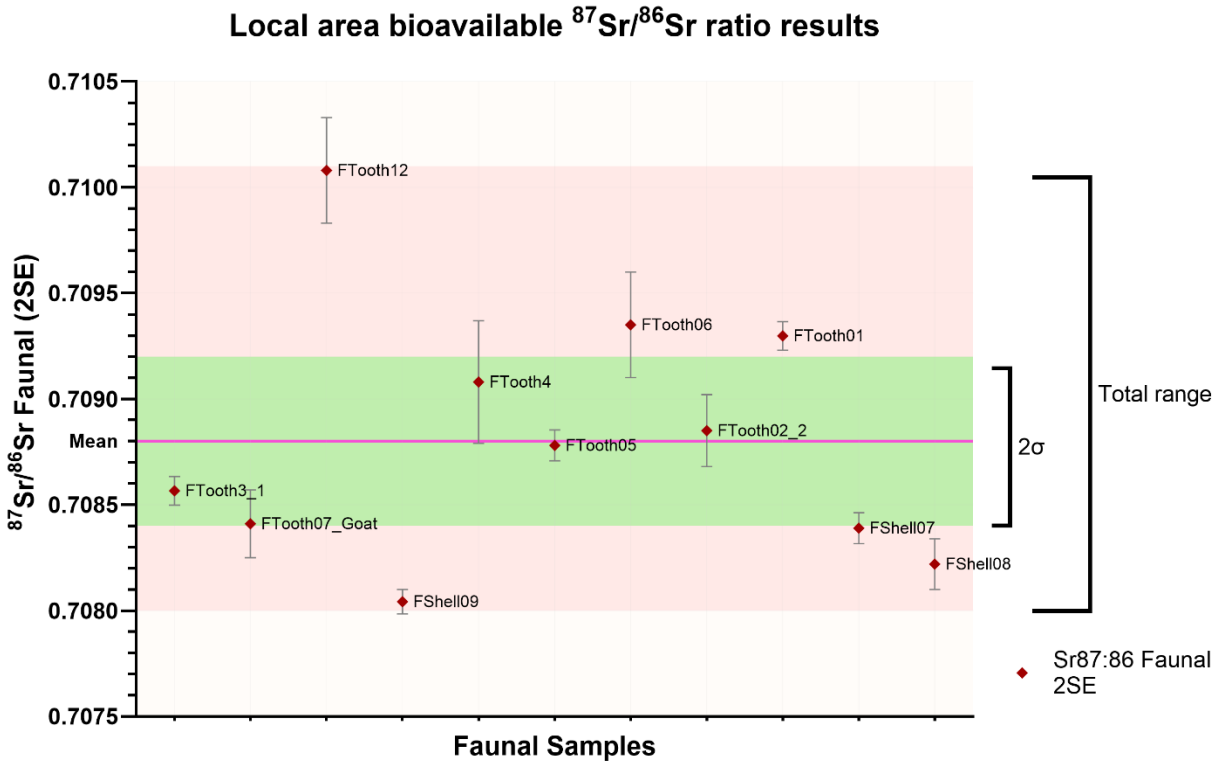


Figure 4. Local Bioavailable ^{87}Sr:^{86}Sr plot. Individual faunal values are depicted with standard error bars. Mean: 0.7088 ± 0.0001797 (1σ); total range: 0.7080 – 0.7101; 95% CI range: 0.7084 – 0.7092

Bulk strontium isotope ratios of the faunal samples ranged from 0.7080 to 0.7101, with a mean of 0.7088 ± 0. 0.0001797 (2σ). The local range (0.7084 – 0.7092) was determined using the upper and lower confidence interval of the mean at 95% confidence in keeping with methods used in other published studies (Perry et al., 2017; Price et al., 2002) (Figure 5). Normal

distribution of samples was confirmed using four statistical tests the results of which can be viewed in Appendix #C3 however, visual checks of the histogram plot (Figure 5a) in combination with a small sample size make it difficult to confirm with absolute confidence the normality of these results, calling into question the validity of the confidence interval. Skewness was identified at 0.7973 consistent with positively skewed data, and a kurtosis of 0.4814 indicating that some degree of the variance is a result of a few large deviations from the mean, though not so much as to extend beyond the standard definition of approximately normal distribution (<1.00) (Kaltenbach, 2012; Motulsky, 2026b*)*. The difference in probability that the distribution of the results are normal versus lognormal indicate by a small degree that the data is more likely to be lognormal (% difference of 0.16%). However, given the minimal difference in probability for either distribution combined with the other factors discussed above it was decided that this study would proceed with the confidence interval of the mean as planned, with the caveat that the confidence interval accuracy **would be greatly** increased with future analysis of a larger sample size. For a larger explanation of the limitations of this approach see ***Chapter 5: Discussion***.

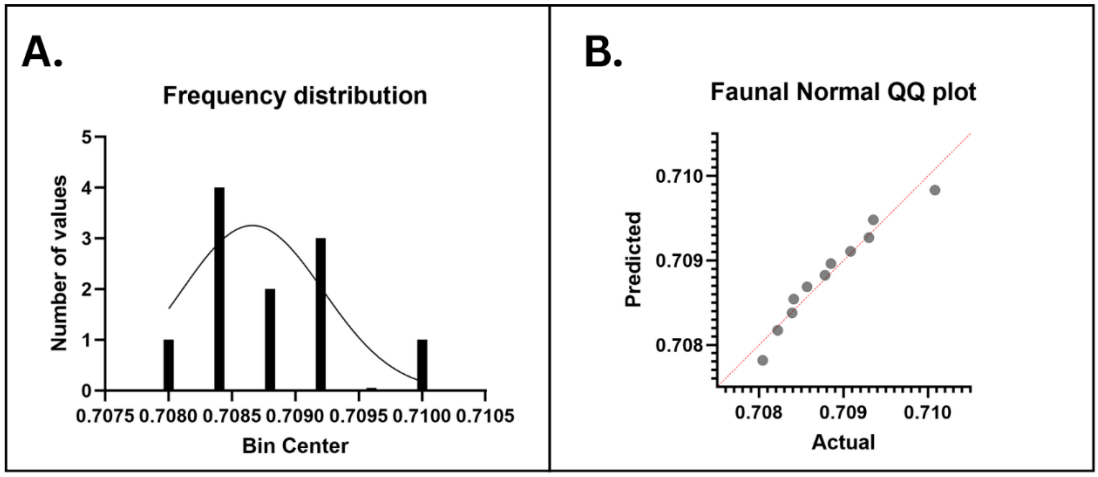


Figure 5. Normality plots. A. Histogram of Faunal sample distribution, n = 11, bin size = 0.0004; B. Faunal data Normality QQ plot

4.2 Locality of samples

The human sample population data was divided into 3 categories: Primarily local, Primarily non-local, and Variable (Figure 6). Primarily local individuals had a 95% confidence interval which fit within the local bioavailable range, whereas primarily non-local individuals had a 95% confidence interval which did not fall under the bioavailable strontium range. Non-local individuals had a 95% confidence interval in which either the upper or lower margin fell into the bioavailable range, while the rest of the interval fell outside of the range. The homogenization of the total variation of values into a mean consequently reverts samples to a bulk representation of locality over tooth development period. Additional qualitative evaluation of time and periodicity of non-local/local mobility over time was compared to the designation indicated by each sample's means to evaluate the extent of mobility using a longitudinal rather than static average.

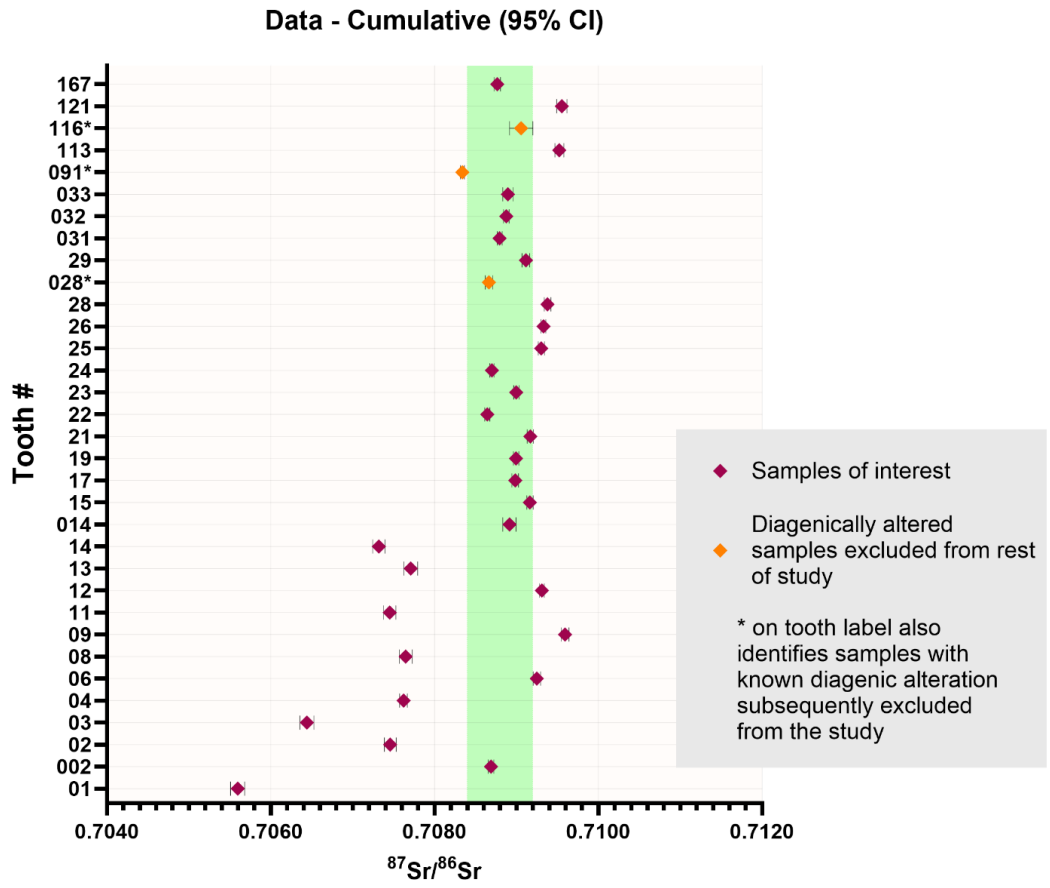


Figure 6. Plot of mean $^{87}Sr/^{86}Sr$ by sample with 95% Confidence interval bars, Calculations excluded values of probable instrumental interference and post-mortem cracks in the enamel. Local Bioavailable Sr range is denoted by the green bar.

The moving/longitudinal averages of each sample represent the average of the dataset over the span of the growth period rather than as one single moment in time. While each laser ablation is ~ 10µm apart, the laser occasional took the first 1-2 points such that the distance is not in an increment of 10 µm. As such while the smoothed trendlines are fairly reliable, individual values should be considered approximate as the average for the first points may not represent the same distance as other sections of data where all data points are taken 10µm apart. For each of the data sets ≤ 2 laser points at the beginning of the total track were affected, and in many cases these points were eliminated due to suspected instrumental artifacts at the start and

end of sample lines and, as such, do not affect the overall smoothed data. Any cracks in the teeth were identified and excluded with up to 100µm of additional data also excluded surrounding the point so each crack would have a 'cushion' in the case of potential post-mortem contamination as an extra precaution, these areas are noted and highlighted in the plots. Any suspected instrumental artifacts, outlier/significant spikes or drops in data at the beginning and/or end of the laser line were pruned from the data and are not shown on the plots presented.

With respect to the accuracy of the ages of development and their association with the structure of mature enamel it is difficult to associate any exact year of development to a particular point of sampled enamel. The sampling rationale assumes that the initiation of development begins at the apex of the tooth, with cascading initiation of ameloblast activity toward the cervix of the enamel. However, due to various factors including variable development between individuals, human limitations in sampling, accessibility of the enamel apex, and post-mortem alteration, it is not possible to concretely state the exact year and day of a child's development using the logic of spatiotemporal sampling. As such, developmental periods are defined by their known typical developmental timeline by tooth type, and subsequently approximate timing of development within those parameters for each individual is determined by accepting the assumption that enamel develops at a rate of ~ 4µm per day. Intervals of ~365 days of growth are represented as ~ 1460 µm (4µm/day x 365 days/year) each on the plots and give a rough estimation of the number of years of growth represented by the data presented here.

4.3 Incisors

Table 5. Information table for Incisor samples and results

Tooth #	***Tooth type***	***Confidence interval (95%)***	***Locality***	***Developmental period of tooth type***	***Approximate length of time represented within the development period***
113	I	0.7095- 0.7096	Non-local	~ 3-5 months - ~4 – 5 years	~ 5 years
167	URI2	0.7087 - 0.7088	Local	~ 3-5 months - ~4 – 5 years	~ 2 years

Incisors represented < 7% of the total sample population analysed in this study (Table 5), excluding the 3 diagenically altered control samples and typically have a period of development between the ages of ~ 3 months to 5 years. . Tooth #113, an adult incisor, was categorized as non-local and represents a development period ~ 5 years. Tooth #167, a second upper right incisor, was categorized as local, and with ~ 2 years of development represented.

4.3.1 Non-Local

Tooth #113 (Figure 7) trends downward overall, toward the local range over the ~ 4 year development period, with values settling more densely around the local mean in the last half of the developmental period. The spread of the raw data around the smoothed moving average also appears to be reduced in this period in comparison to the data in the former half of development. However, compared to other samples (See Tooth #21) the range of raw data points around the

smoothed moving average does not seem to be outside of the norm in later years, making it arguable that the larger spread in earlier childhood may be the more notable difference between this and later developmental periods. Despite being categorized as non-local, early developmental smoothed and raw data points hover above or just below the upper local Sr values, settling more closely to the local mean as the child approaches the end of the period represented. These data do seem to be trending toward the lower bounds at the end of the developmental period seen here, however, there is not a clear picture of whether the values will continue to move back outside of the local range. The early childhood values appear to be skewing the mean outside of the local range, rather than the actual length of time spent outside of the local area. Of the 750 points taken, 513 total points fell outside of the local range indicating that ~ 31% of the period was within the local range.

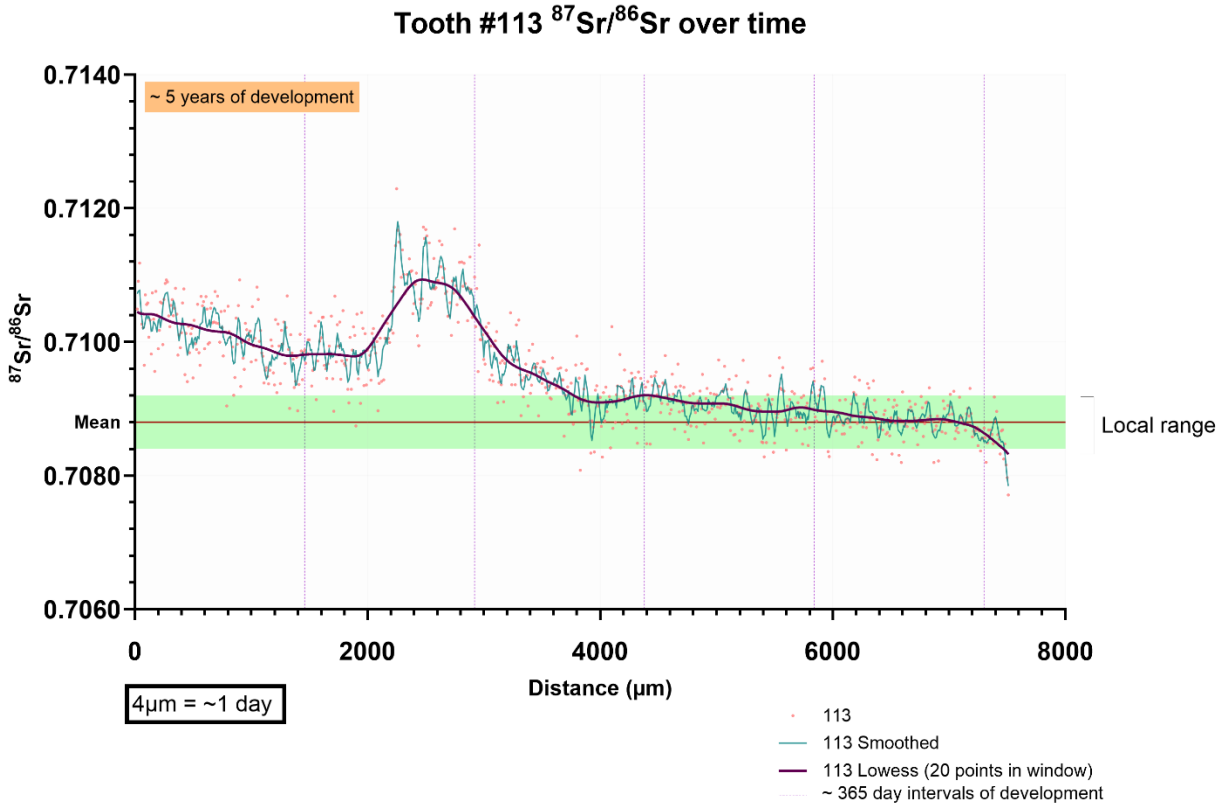


Figure 7. Timeseries plot of Tooth #113. Includes exact spot ratio data (113), 2nd order smoothing for short term trends (113 Smoothed), and fine averaging for long term trend representation (113 Lowess).

4.3.2 Local

In contrast, Tooth #167 (Figure 8) follows a much more expected pattern of what we would perceive to be local and represents about two years of development. While a short period of time at the beginning and end of the tooths development fall outside of the local range, the majority of short and long term smoothed moving averages in this time period fall within the local range. However, this tooth represents a smaller period of time, and the two samples are not easily comparable given that the two year period in which the Tooth #167 is averaging in the

local range could easily be equated to the 2.5 year period in which Tooth #113 also fell within/around the local range, despite also having a significant period of time spent non-locally.

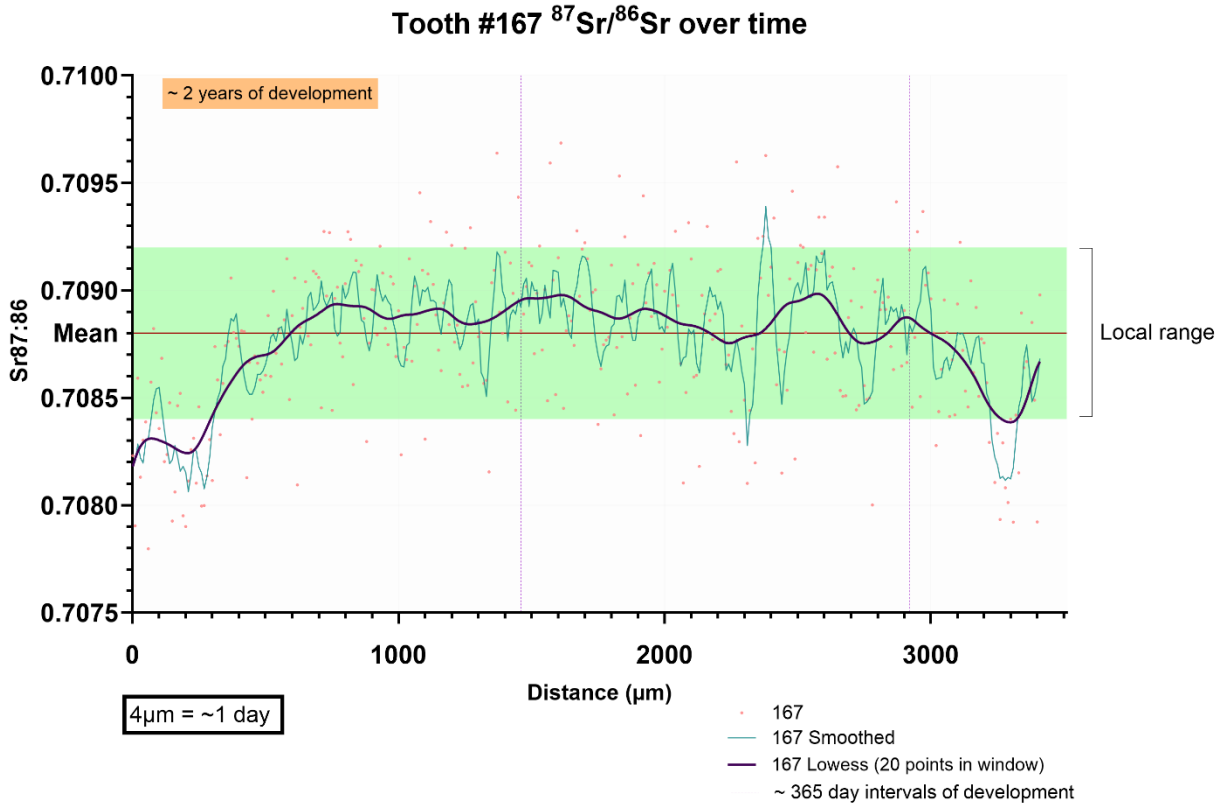


Figure 8. Timeseries plot of Tooth #167 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (167), 2nd order smoothing for short term trends (167 Smoothed), and fine averaging for long term trend representation (167 Lowess).

4.4 Premolars

Table 6. Information table for premolar samples and results

Tooth #	***Tooth type***	***95% Confidence interval***	***Standard Error Margin of Mean***	***Locality***	***Developmental period of tooth type***	***Approximate length of time represented within the development period***
24	LLP3	0.7087 - 0.7087	1.309e-005	Primarily local	~1.8 years – ~5/6years	~ 4 years
25	LLP3	0.7093 – 0.7093	1.990e-005	Primarily non-local	~1.8 years – ~5/6years	~ 4 years
26	LLP4	0.7093 – 0.7094	1.470e-005	Primarily non-local	~1.8 years – ~5/6years	~ 3 years
28	URP3	0.7093 – 0.7094	2.119e-005	Primarily non-local	~1.8 years – ~5/6years	~ 2 years
29	ULP3	0.7091 – 0.7092	2.407e-005	Variable locality	~1.8 years – ~5/6years	~ 3 years
033	URm2	0.7088 – 0.7089	3.239r-005	Primarily local	~ 18 weeks in utero	~ 1 year
121	m	0.7095 – 0.7096	2.001e-005	Primarily non-local	~15 weeks in utero - ~0.5 years	~ 2 years

The premolars analyzed for this study (Table 6) included both upper and lower permanent third and fourth premolars and a developmental period generally representative of early childhood (1.8 to 5/6 years of age), though this is also dependent on the individual teeth and the length of laser ablation we could reasonably achieve. Also included are two deciduous molars representative of mostly in-utero development. Of the five total adult premolars, three teeth are primarily non-local, one is primarily local, and one has indications of variable locality. The deciduous molars include one primarily local, and one non-local.

4.4.1 Local

Tooth #24 (Figure 9) had a range of local and non-local values throughout the period of development represented by the data (~ 4 total years) however, the short and long term moving averages both fell primarily within the local range with no notable patterns of mobility between the local and non-local range for any particular time period. Rather, the individual data points fell sporadically outside of the local range with Sr values that were both greater and less than the local bounds surrounding 95% interval. The subsequent moving averages demonstrate some trends in value changes however, these all fall within the local range so it is not possible to place a particular explanation for these trends in relation non-local or local mobility.

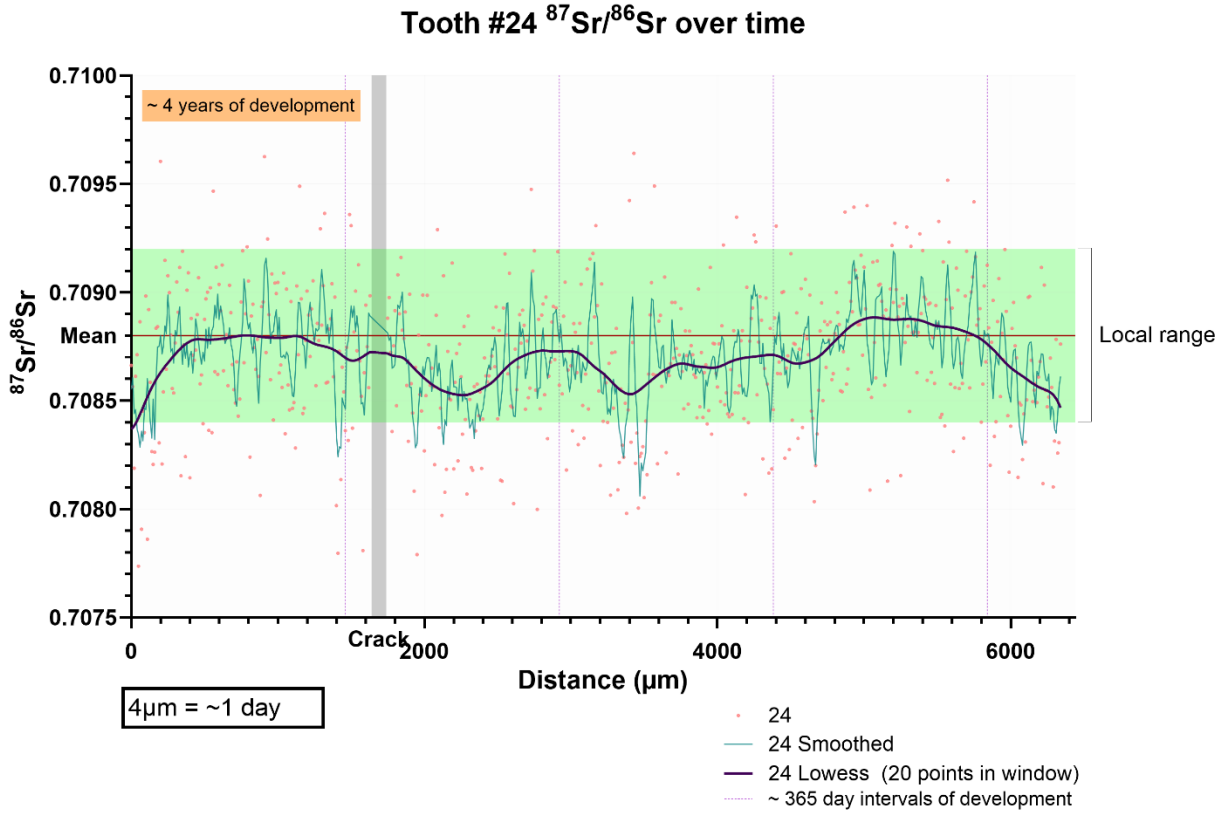


Figure 9. Timeseries plot of Tooth #24 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range.

4.4.2 Non-local

The only deciduous molars in this sample set are Tooth #121 (Figure 10) and Tooth #033 (Figure 11), and these deciduous molars typically begin development in utero at approximately 15 weeks typically maturing around six months post-natal (Hillson, 2024). Tooth #121 represents about two years of development and is consistently non-local, with few data points entering the local range while Tooth #033 represents about one year of development and appears to be the opposite, with both moving averages and raw data points falling almost entirely in the local bioavailable range. No notable trends or patterns between local and non-local ranges are noted for either sample, and they are both fairly stable over time.

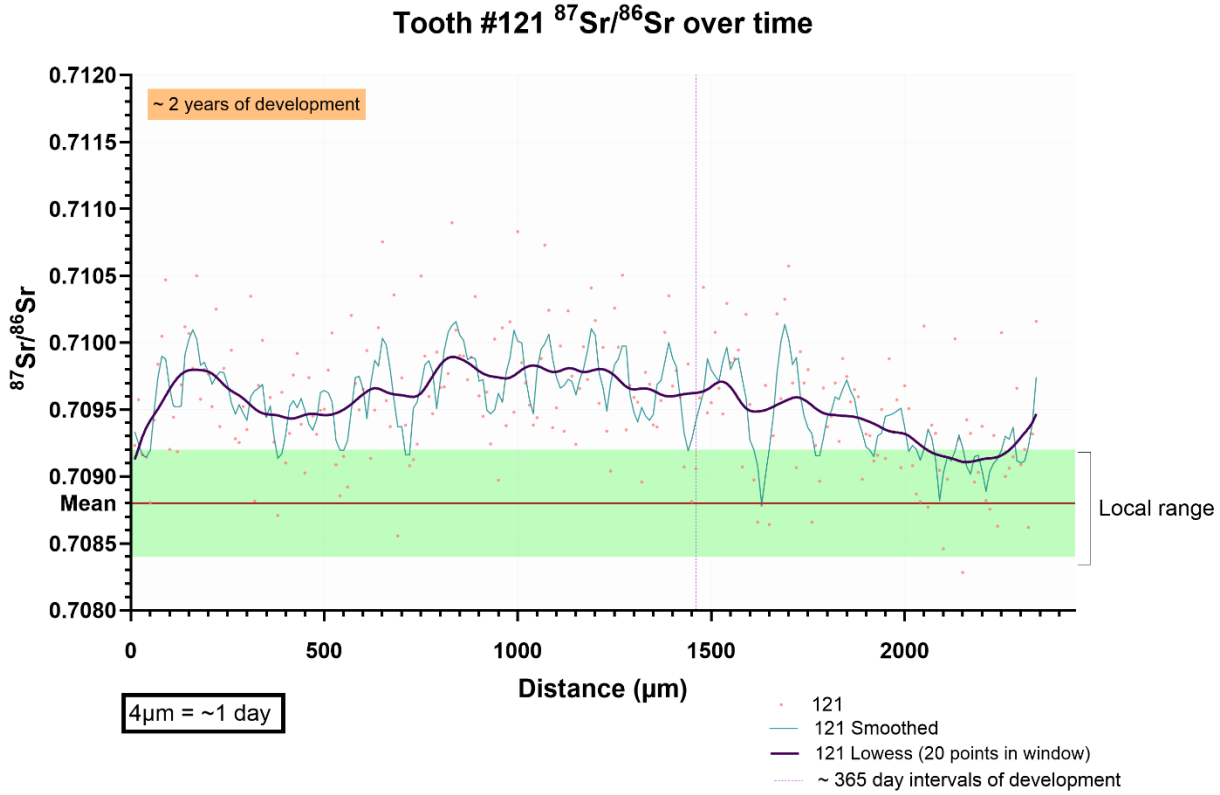


Figure 10. Timeseries plot of Tooth #121 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (121), 2nd order smoothing for short term trends (121 Smoothed), and fine averaging for long term trend representation (121 Lowess).

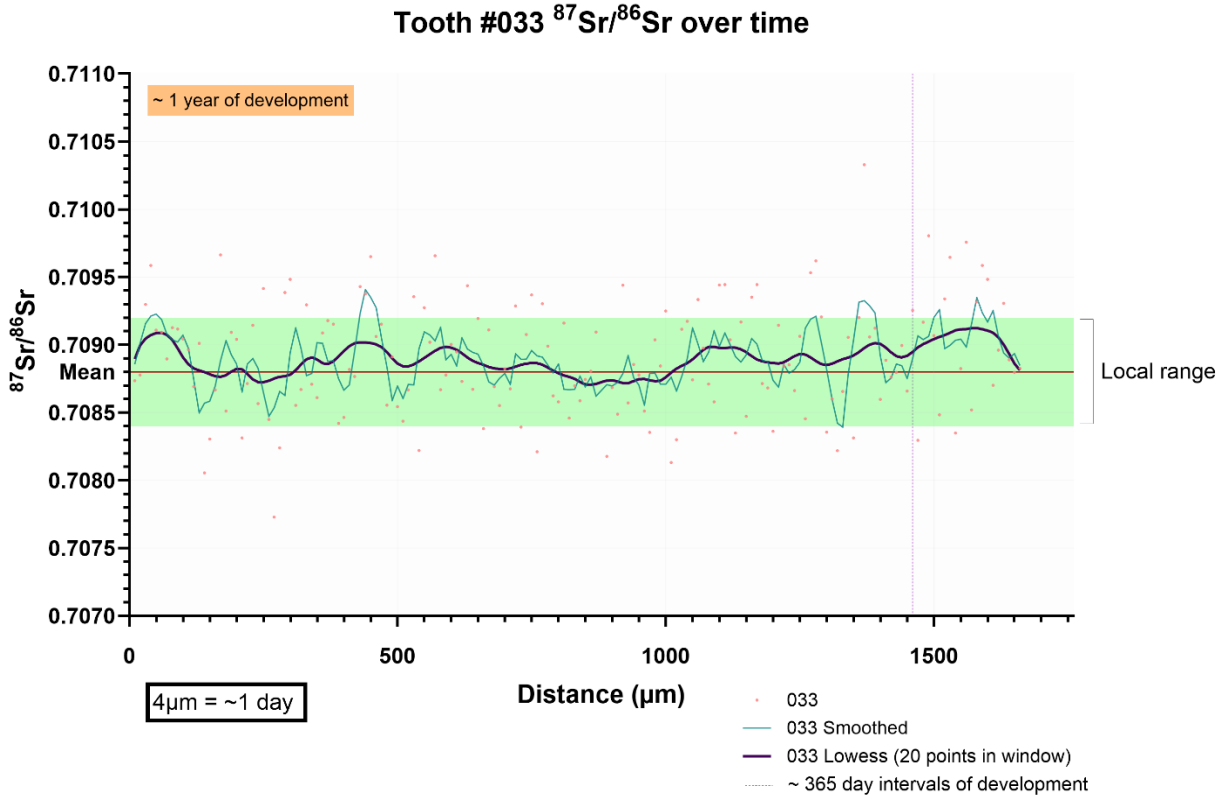


Figure 11. Timeseries plot of Tooth #033 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (033), 2nd order smoothing for short term trends (033 Smoothed), and fine averaging for long term trend representation (033 Lowess).

Teeth #25, #26, and #28 all have 95% confidence intervals which fall outside of the bounds for local bioavailable strontium and represent the non-local adult premolar samples of the sample population. Among these three teeth, despite some movement into the bioavailable range, most changes in the short and long term moving averages occur outside of the local zone.

Tooth #25 (Figure 12) represents about 4 years of the total developmental period and appears to be entering the upper bounds of the local bioavailable range more frequently than the other samples, the length of time spent is typically less than ~6 months at a time. However, the smoothed averages seem to hover just above or around the upper bounds of the local range, with

32% of data points still falling within the local range. There may be a possible trend toward the local range more consistently in the terminal portion of the data however, this is uncertain due to a lack of further data from the enamel. Ultimately the movement between local and non-local areas is not consistent enough to conclude that there is any distinct pattern.

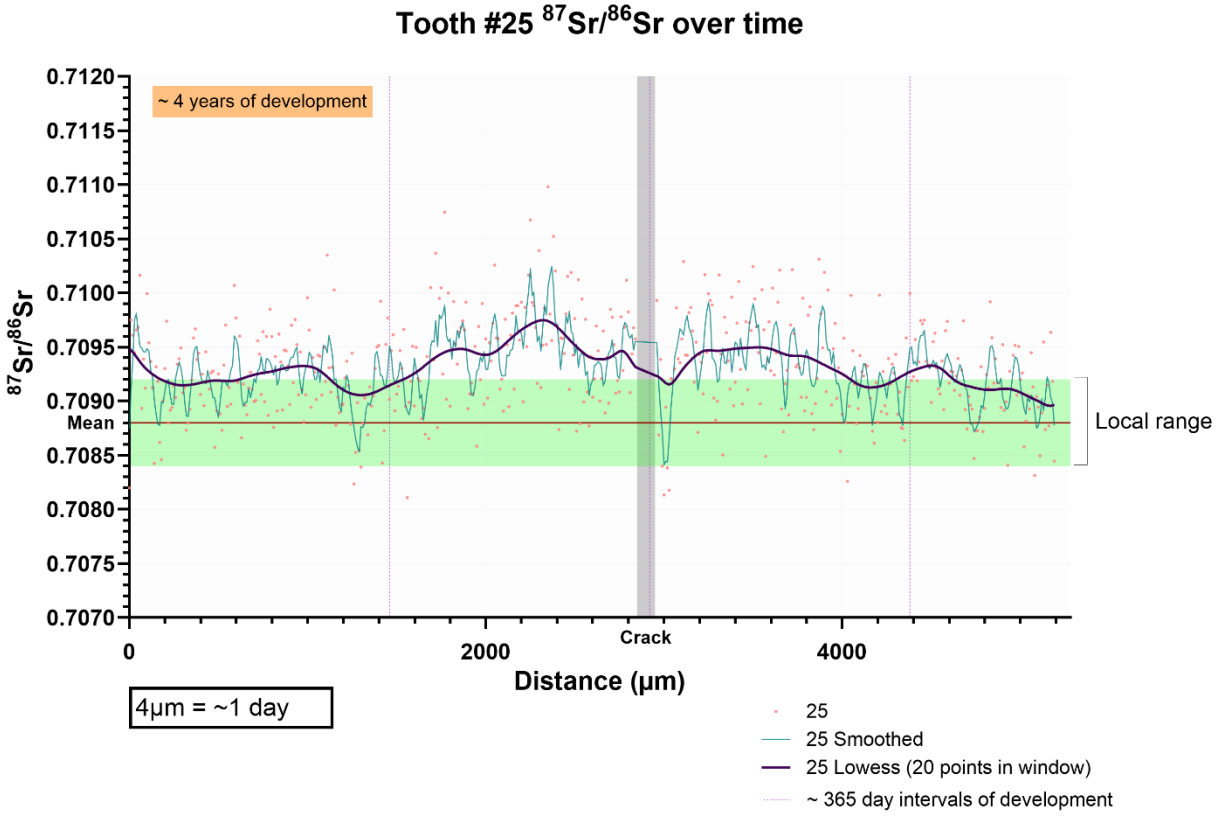


Figure 12. Timeseries plot of Tooth #25 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (25), 2nd order smoothing for short term trends (25 Smoothed), and fine averaging for long term trend representation (25 Lowess).

Tooth #26 (Figure 13) represents approximately 3 years during development and appears to have spent the majority of their time outside of the local area, with indications of a possible move out of the local area initially and a move back in to the local area for a short period of time at the end of the growth period. Subsequent movement out of the local area again by the end of

the growth period represented in this sample is noted. Similarly to Tooth #25, the data points do not fall entirely outside of the local area, though the short- and longer-term smoothed lines do seem to fall less frequently into the local range. Any stray points that do appear in the local area stay, for the most part, above the mean of the local area.

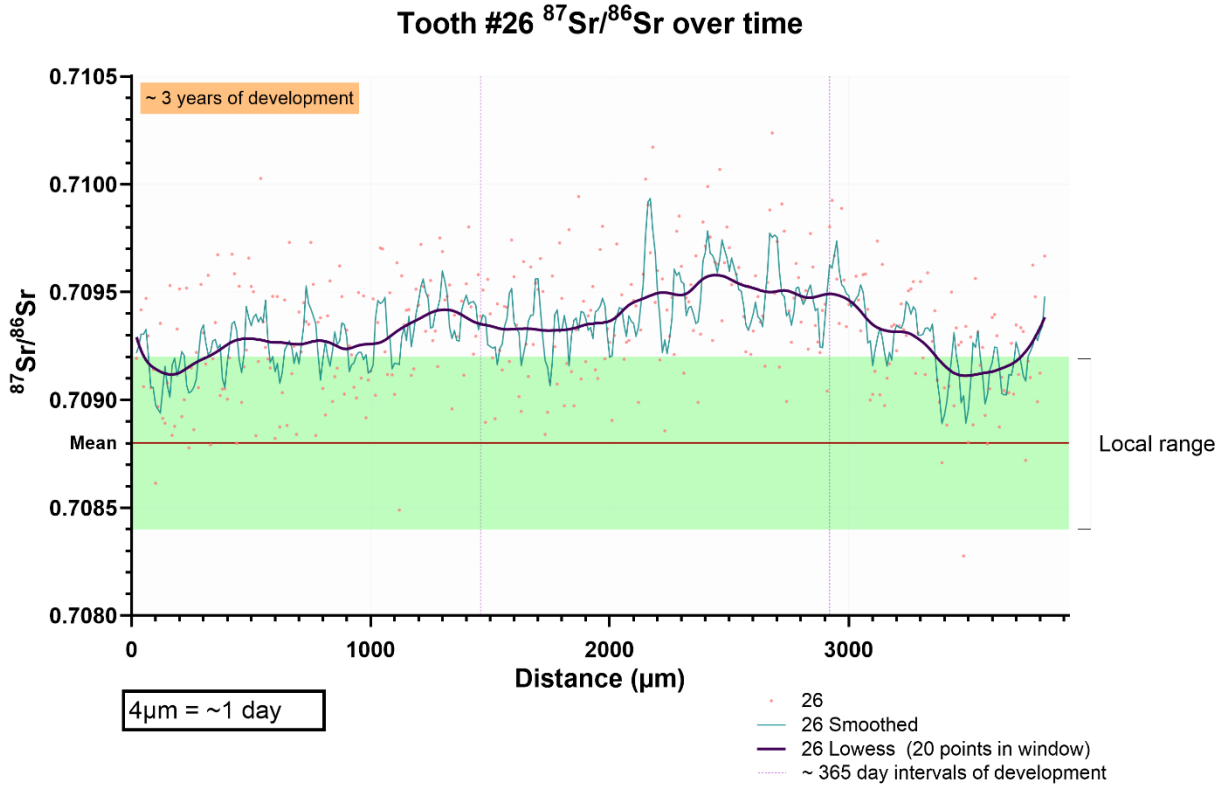


Figure 13. Timeseries plot of Tooth #26 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (26), 2nd order smoothing for short term trends (26 Smoothed), and fine averaging for long term trend representation (26 Lowess).

Tooth 28 (Figure 14) represents approximately 3 years of the total development period, and presents a somewhat more extensive association with the local area. The short term

smoothed trendline indicates that the data mostly falls within the upper margin of the local zone in the beginning of the period, though fairly sporadically. Following this period the rest of the ratios trend upward and the long term moving average stays above the local range for over approximately one year. Again, at the end of the period represented there is increased variability in the shorter term average, which drops four more times into the local range, though the longer term average does re-enter the local range, possibly due to the larger range in data spikes.

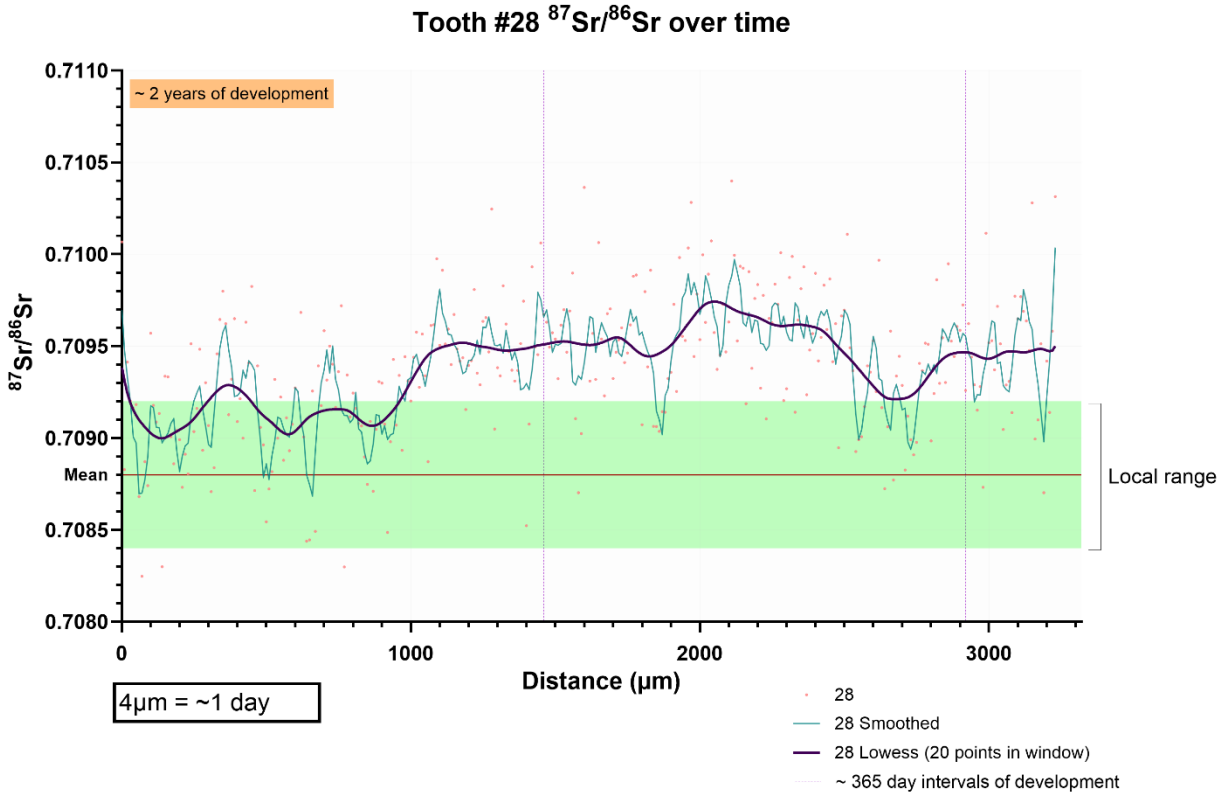


Figure 14. Timeseries plot of Tooth #28 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (28), 2nd order smoothing for short term trends (28 Smoothed), and fine averaging for long term trend representation (28 Lowess).

4.4.2 Variably local

Despite being variably local based on the confidence interval of its mean, Tooth #29 (Figure 15) appears to have a similar trajectory as the non-local samples, with a somewhat more equal distribution of non-local/local points. Representing approximately three years of the incisor developmental period, this sample's non-local values account for 56% of the total data points, while 44% fall within the local range, though the short term average seems to indicate consistent fluctuations in ratios throughout the sample the wide spread of individual data points is not suggestive of consistent movement in the short term. It is possible that the average may simply be skewed toward larger spikes in raw data creating the visual implication of short term movement. The overall trend of this data indicates longer (~0.5-1 year) periods of change as opposed to short term seasonal patterns of movement with the period of non-local values starting about halfway through the data set until the final third of the ratios steeply decline to the local range for another approximately half year period.

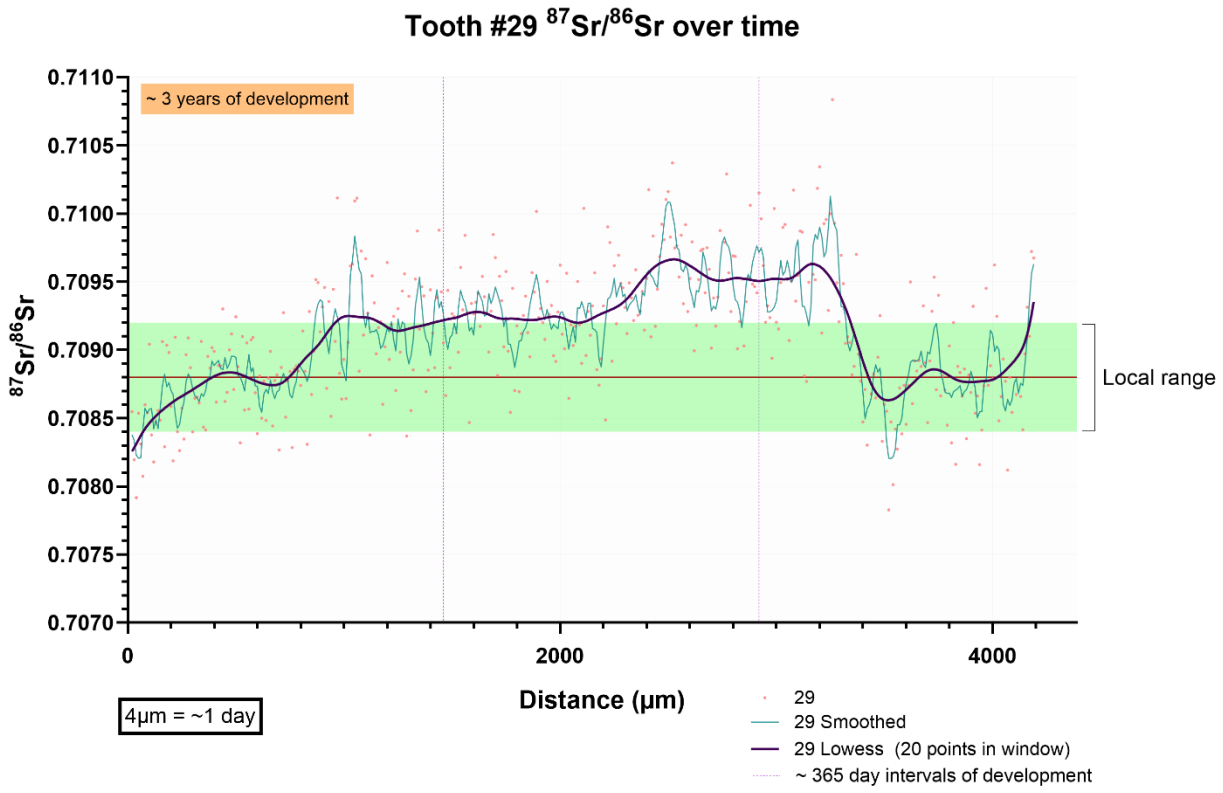


Figure 15. Timeseries plot of Tooth #29 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (29), 2nd order smoothing for short term trends (29 Smoothed), and fine averaging for long term trend representation (29 Lowess).

4.5 First molars

Table 7. Information table for first molar samples and results

Tooth #	***Tooth Type***	***95% Confidence interval***	***Standard error Margin of Mean***	***Locality***	***Developmental period of tooth type***	***Approximate length of time represented within the development period***
002	L?M1	0.7087 – 0.7087	1.678e-005	Primarily local	~ 30 weeks in utero - ~ 3 years	~ 3 years

032	UR M1	0.7088 – 0.7089	1.762e-005	Primarily local	~ 30 weeks in utero - ~ 3 years	~ 3 years
014	M	0.7088 – 0.7090	4.063e-005	Primarily local	~ 30 weeks in utero - ~ 3 years	~ 1 year
031	UR M1	0.7088 – 0.7088	1.498e-005	Primarily local	~ 30 weeks in utero - ~ 3 years	~ 2 years
01	LL M1	0.7055 – 0.7057	4.391e-005	Primarily non-local	~ 30 weeks in utero - ~ 3 years	~ 3 years
02	LL M1	0.7074 -0.7075	3.686e-005	Primarily non-local	~ 30 weeks in utero - ~ 3 years	~ 4 years
03	UL M1	0.7064 – 0.7065	4.312e-005	Primarily non-local	~ 30 weeks in utero - ~ 3 years	~ 3 years
04	UL M1	0.7076 – 0.7077	2.355e-005	Primarily non-local	~ 30 weeks in utero - ~ 3 years	~ 3 years
06	UR M1	0.7092 – 0.7093	2.281e-055	Primarily non-local	~ 30 weeks in utero - ~ 3 years	~ 3 years
08	LR M1	0.7076 – 0.7077	3.966e-005	Primarily non-local	~ 30 weeks in utero - ~ 3 years	~ 3 years
09	LL M1	0.7095 – 0.7096	2.425e-005	Primarily non-local	~ 30 weeks in utero - ~ 3 years	~ 3 years
11	UR M1	0.7074 – 0.7075	3.785e-005	Primarily non-local	~ 30 weeks in utero - ~ 3 years	~ 3 years

Of the 13 first permanent molars analyzed (Table 7) which represent a total developmental period between ~ 30 weeks in utero to ~ 3 years old (Hillson, 2024), 6 were designated primarily local: #002, #014, #031, and #032, while 7 were designated primarily non-local: #01, #02, #03, #04, #06, #08, #09, #11.

4.5.1 Local

Tooth #002 (Figure 16) represents an ~ 3 year span of the total developmental period for first molars and for the most part remained consistently local, with few data points straying from the local range until ~ 1.5 years have passed, when the values begin trending toward the lower margin of the range. Subsequently, the moving average stays consistently in/around the lower margin of the bioavailable range for the rest of the developmental period. Throughout the development of the tooth, however, ~30% of the values still fall outside of the local range despite this perceived stability due to the wide spread of data points.

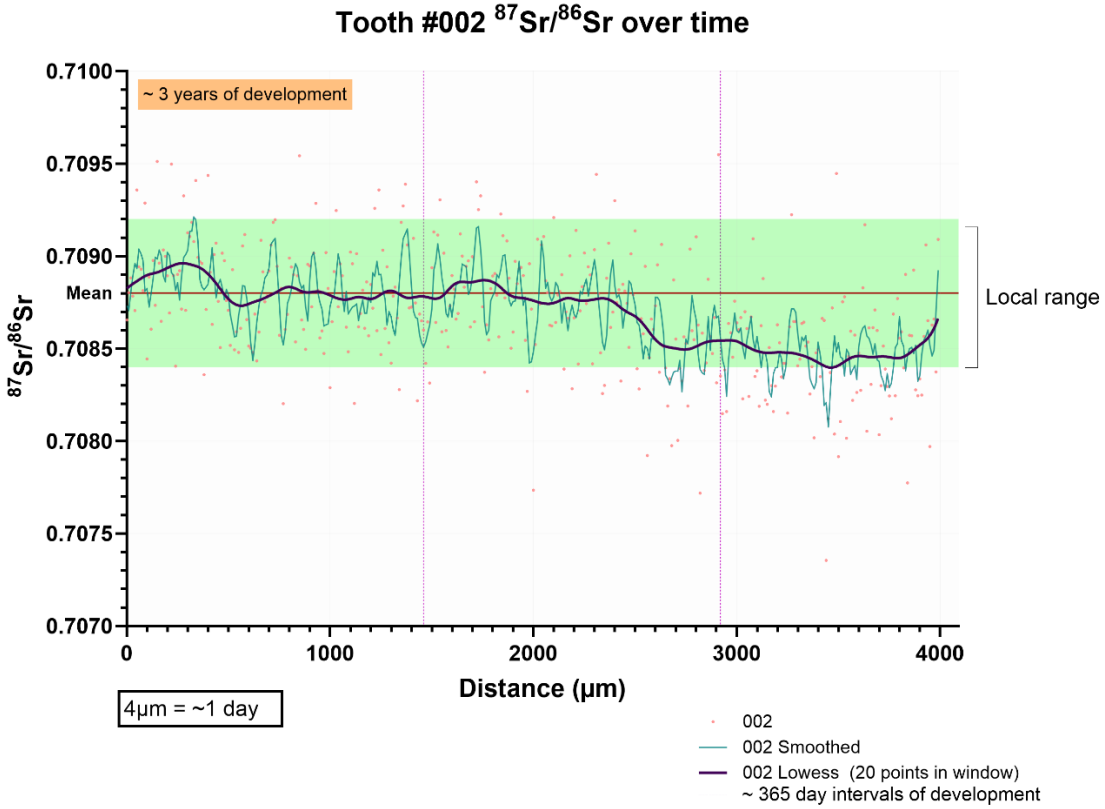


Figure 16. Timeseries plot of Tooth #002 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (002), 2nd order smoothing for short term trends (002 Smoothed), and fine averaging for long term trend representation (002 Lowess)

Tooth #014 (Figure 17) represents a very short development period in comparison to #002, with only ~ 1 year of total growth represented. Fluctuations which cross the local boundary values in are noted, evidenced by both short- and long-term moving averages, though the majority of values remain within the local range. Overall, there is a downward trend toward the local boundary, and the fluctuations could be interpreted as periodical, however it is difficult to assess the reliability of these fluctuations due to the length of time represented, which may appear less significant when compared to the fluctuations seen on other samples with a larger temporal representation.

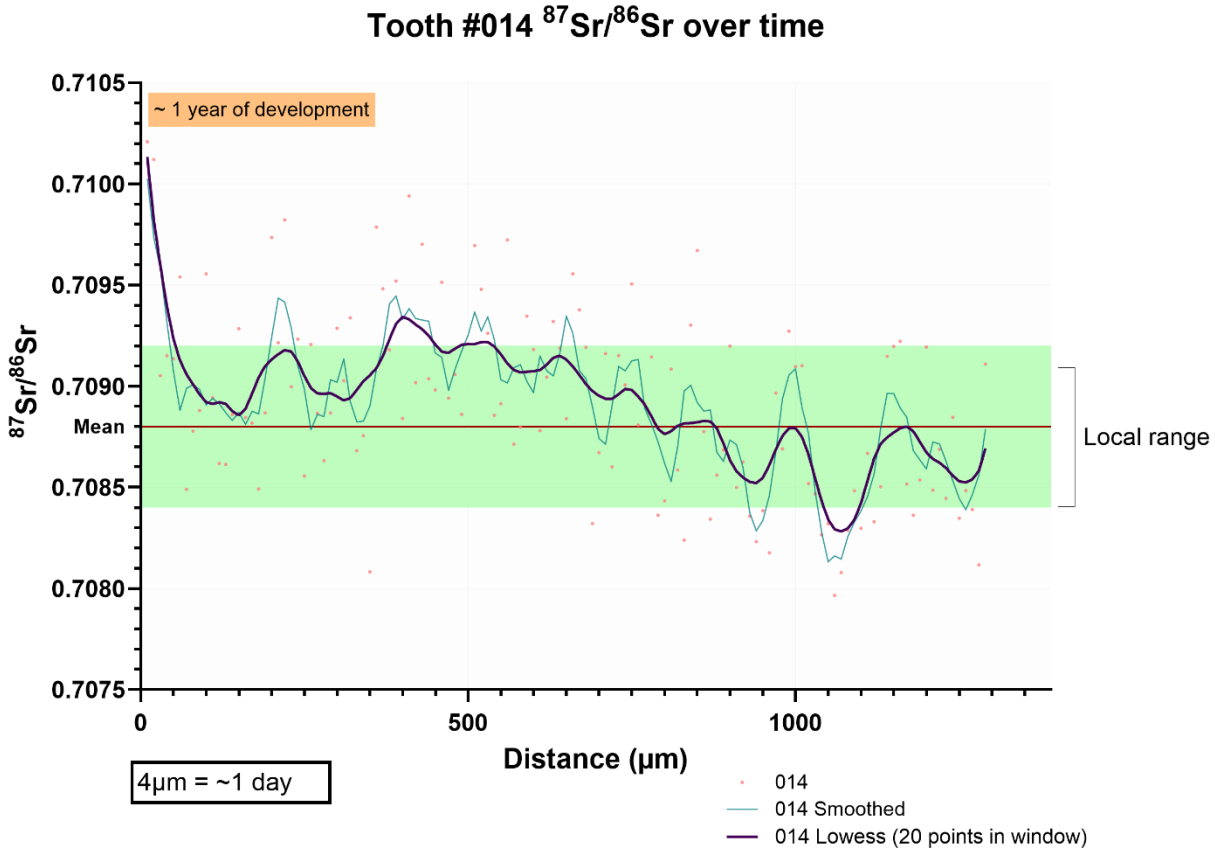


Figure 17. Timeseries plot of Tooth #014 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (014), 2nd order smoothing for short term trends (014 Smoothed), and fine averaging for long term trend representation (014 Lowess).

Teeth #031 Figure 18) and #032 (Figure 19) are the most stable of these samples, lacking the downward trending later portion of the development period represented by the tooth. Tooth #031 remains densely populated around the mean of the local range, with minimal deviation from the local range over approximately 2 years of the total molar development period.

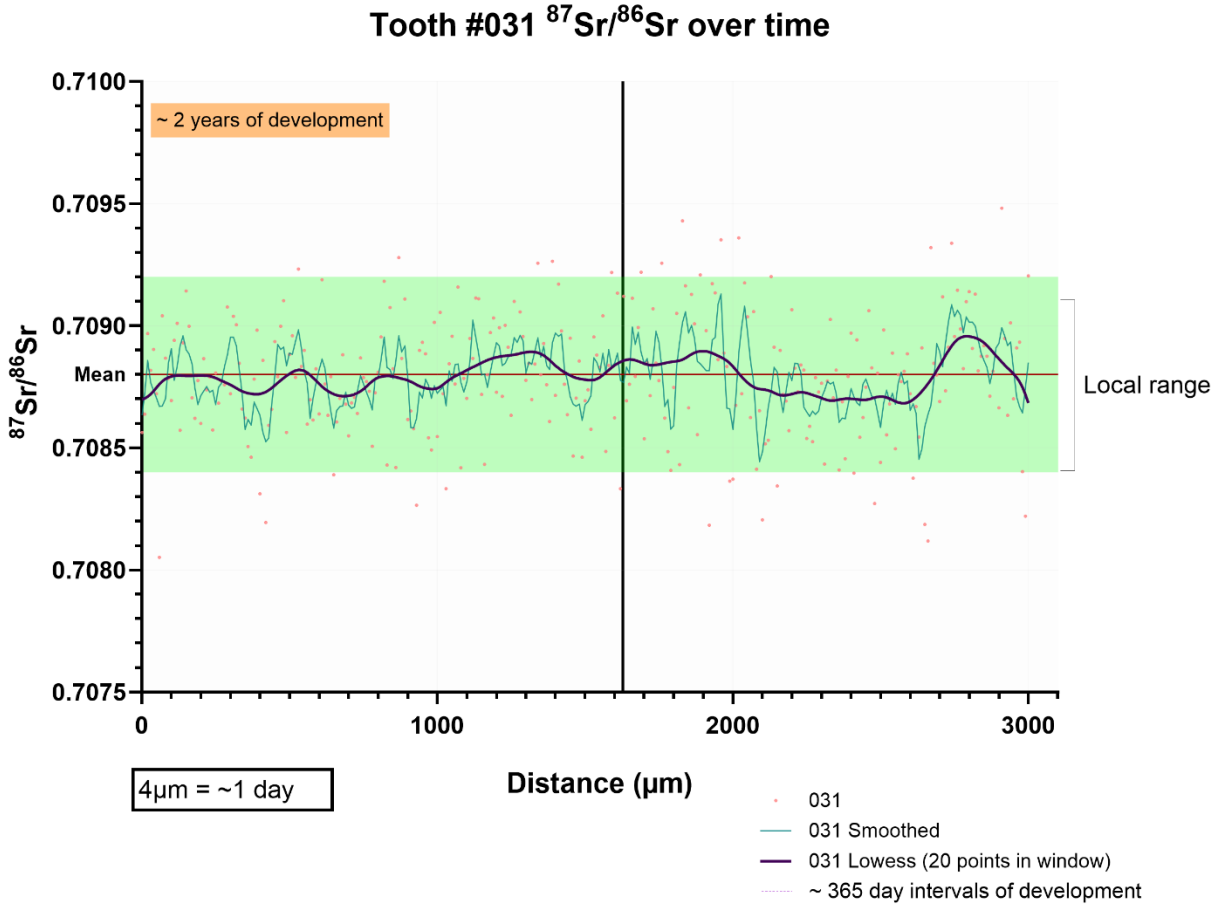


Figure 18. Timeseries plot of Tooth #031 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (031), 2nd order smoothing for short term trends (031 Smoothed), and fine averaging for long term trend representation (031 Lowess).

Tooth #032 (Figure 19) appears to range more widely around the central mean of the local range, however despite the fluctuations there is also no clear long term trend toward either margin, aside from the initial downward trend to the local range and a small drop in values at the end of the development period. ~33% of the values fall outside of the local range, and the majority (99 data points) fall above the range, as opposed to the 27 which fall below the local

range, suggesting a possibly more clear likelihood of movement outside the upper boundaries if non-local movement was occurring in a less chemically visible way.

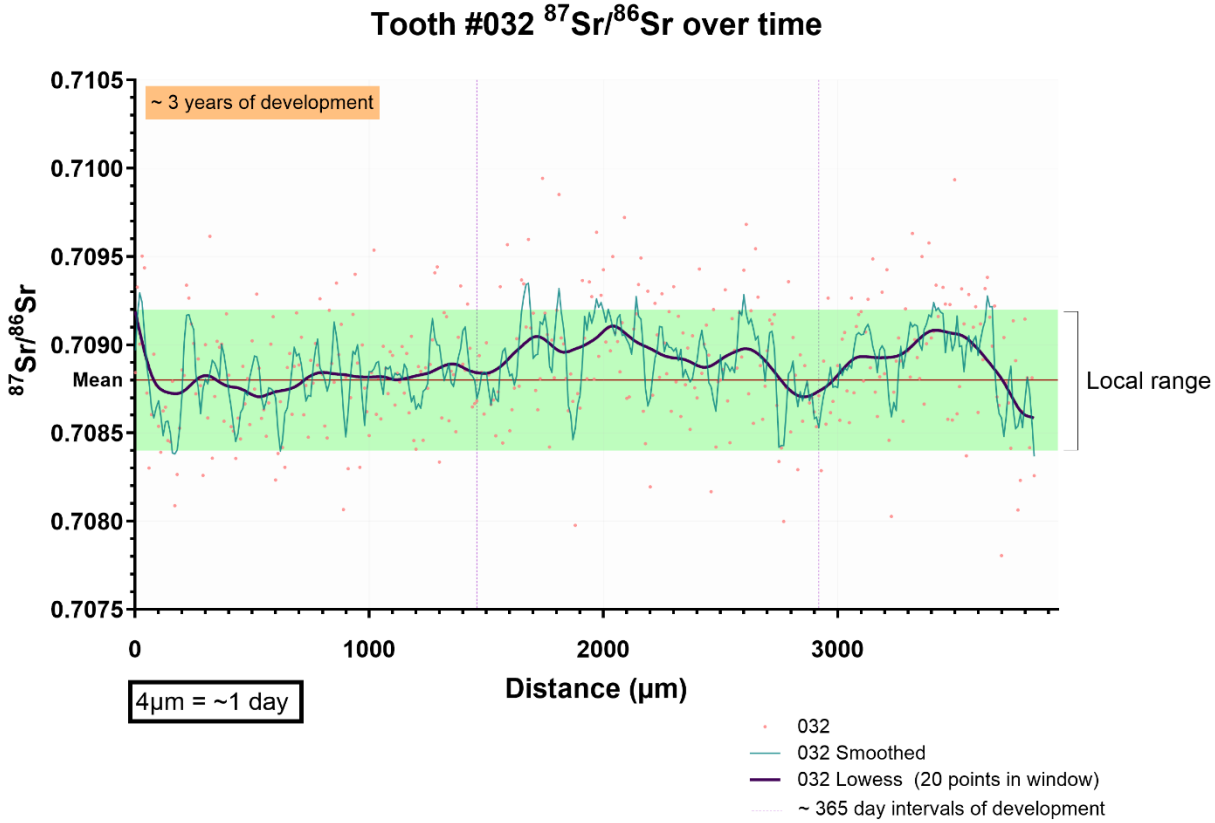


Figure 19. Timeseries plot of Tooth #032 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (032), 2nd order smoothing for short term trends (032 Smoothed), and fine averaging for long term trend representation (032 Lowess).

4.5.2 Primarily non-local

Primarily non-local teeth varied more widely in terms of short- and long-term with more significant fluctuations in long-term moving average over time. Tooth 01 (Figure 20), and 03 (Figure 21) remain almost entirely outside of the local range over the development period of the tooth. Tooth 01 (Figure 20) represents ~ 3 years of the development period and indicates

fluctuations in values of about 0.5 year intervals, though these are not repeated sequences of movement to a specific range. It initially trends sharply downward between 1000µm and 2000µm, after which it remains stable until around 3000µm where the values drop again and then begin to rise throughout the rest of the sample, though not steadily. Notably only two data points fall within the local range, indicating a much clearer division from the local samples although the extremely low ratios are of interest.

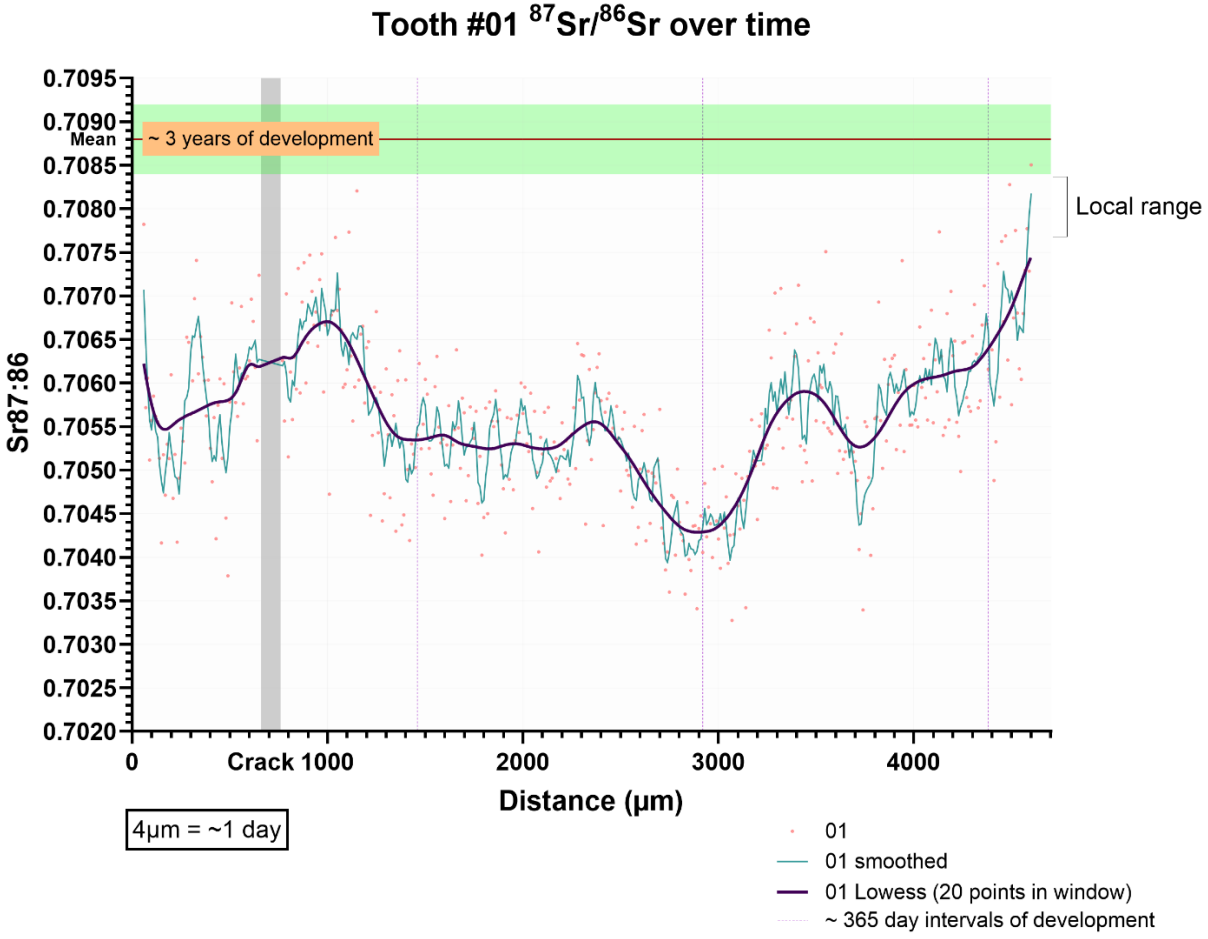


Figure 20. Timeseries plot of Tooth #01 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (01), 2nd order smoothing for short term trends (01 Smoothed), and fine averaging for long term trend representation (01 Lowess).

Tooth #03 (Figure 21) undergoes similar long term ratio fluctuations of ~ 0.5 – 1 year periods of rise and fall throughout the tooths development, with data points falling almost entirely outside of the local range. Similarly to Tooth #01, there are no clear repeating patterns of movement over the course of development, though it does appear that the last year of development represented may suggest that the values are moving back toward the initial ratio values, possibly indicating a return to the original area after > 1 year away. However, the lack of corresponding tooth sample representative of a later developmental period prevents the visualization of later mobilization periods for this individual.

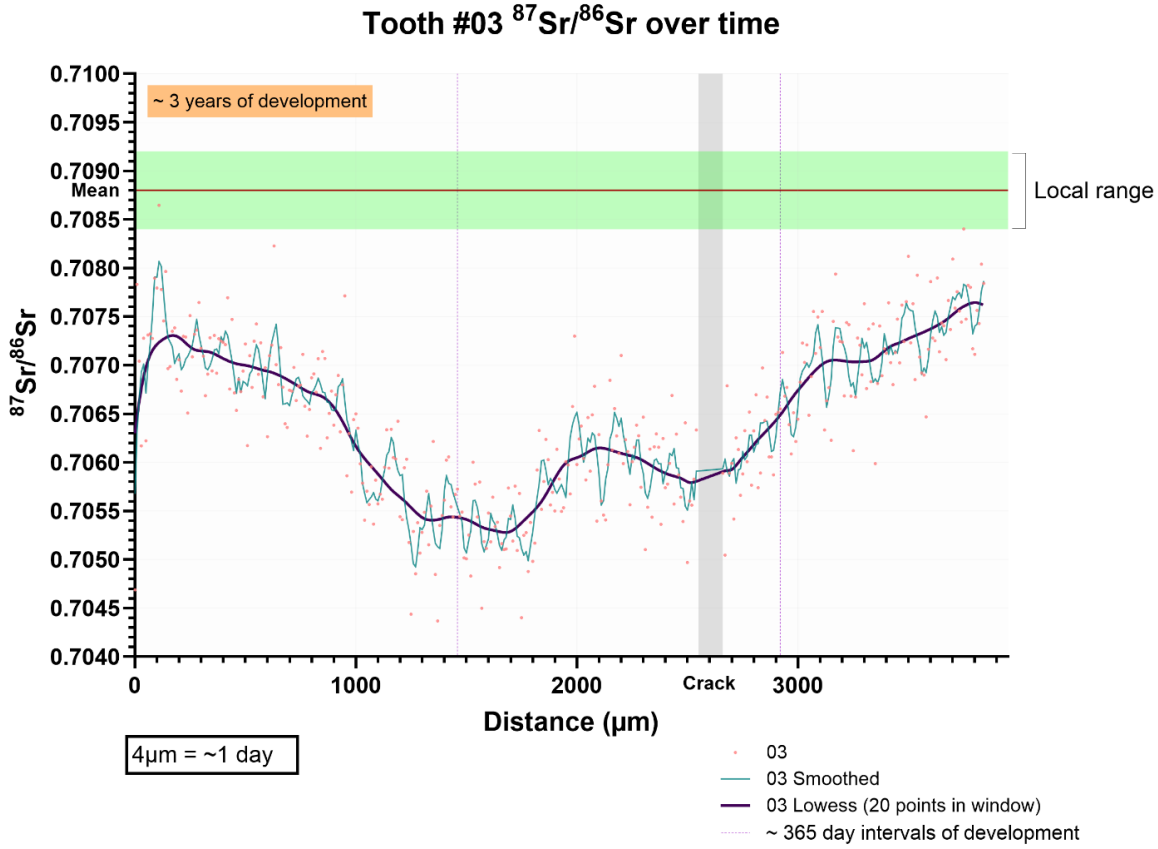


Figure 21. Timeseries plot of Tooth #03 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (03), 2nd order smoothing for short term trends (03 Smoothed), and fine averaging for long term trend representation (03 Lowess).

Tooth #02 (Figure 22) represents approximately four years of the developmental period and trends generally downward over time, before plateauing at around 1500µm, undergoing sustained periods of fluctuation toward or away from the local range over the course of approximately a year. Moving averages indicate ~ one year periods of trend changes occasionally punctuated with sustained stability after change. Values initially began to trend downward at the beginning of the period from the local bioavailable range of values, eventually reaching ~ two thousandths lower than the lower boundary of the local range by the end of the sample.

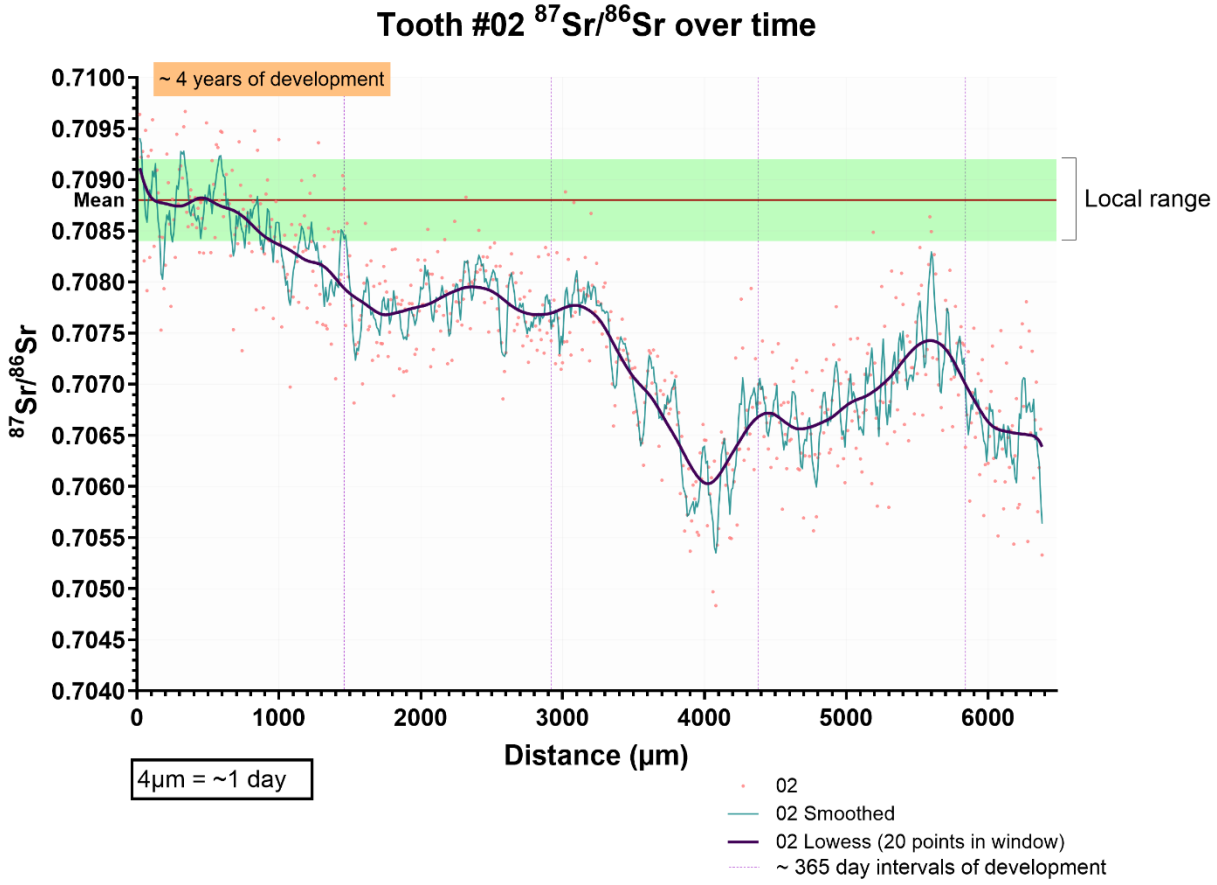


Figure 22. Timeseries plot of Tooth #02 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (02), 2nd order smoothing for short term trends (02 Smoothed), and fine averaging for long term trend representation (02 Lowess).

In contrast, Tooth #04 (Figure 23) is more stable during the approximately 3 year period represented, with the majority downward trending Sr values occurring in the first half year of the development period, subsequently plateauing with somewhat stable moving averages around after ~ 2000µm. While the number of data points entering the local bioavailable range is slightly increased compared to Tooth #02, the amount is negligible, and the short- and long-term moving averages do not enter the local range at any point.

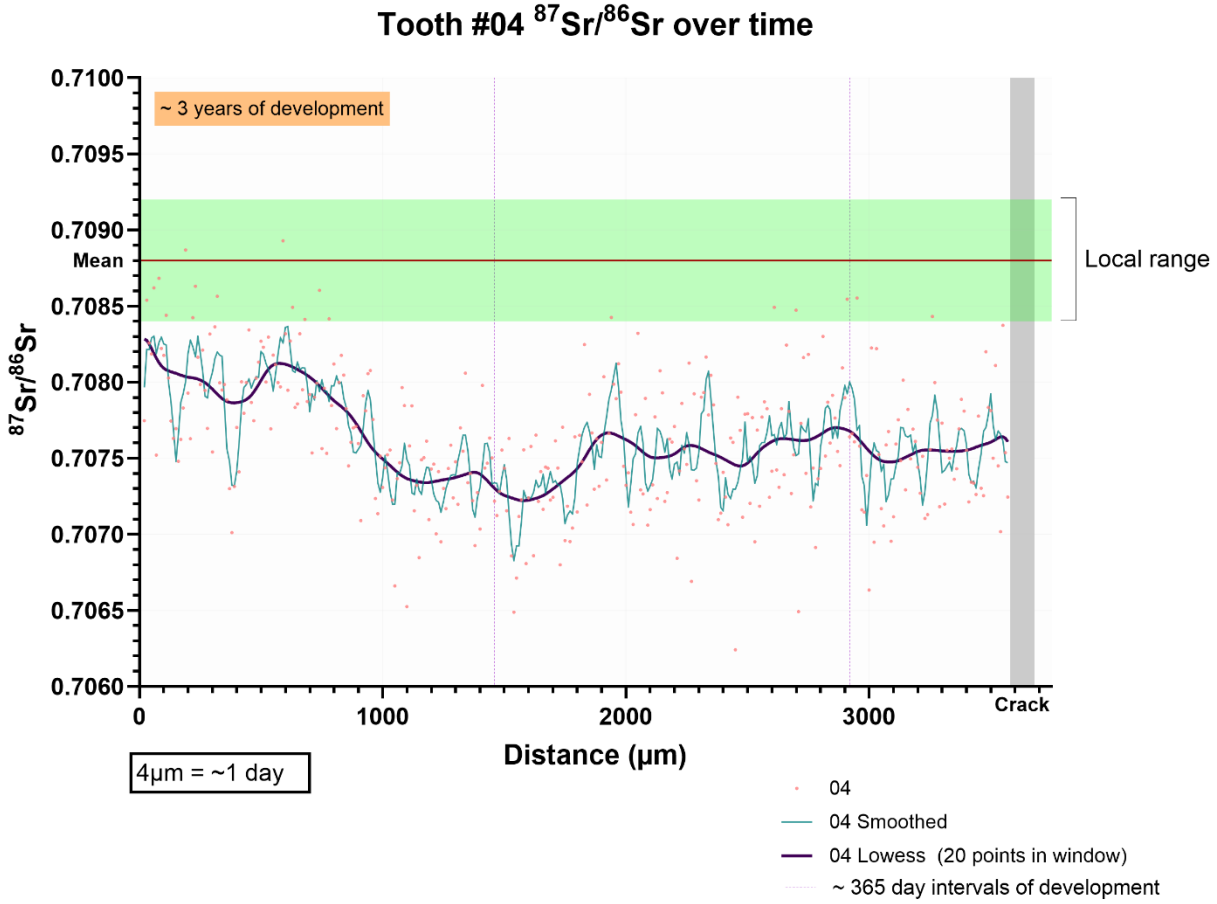


Figure 23. Timeseries plot of Tooth #04 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (04), 2nd order smoothing for short term trends (04 Smoothed), and fine averaging for long term trend representation (04 Lowess).

The following non-local teeth follow the opposite overall trend, with values following a generally upward trend over time.

Tooth #06 (Figure 24) and 09 (Figure 25) have similar periods of fluctuation throughout the development of the tooth over time. Tooth #06 represents approximately 3 years of development and enters the local range the most out of these two, beginning in the local range and continuing to remain at or around the top range of the local bounds with increased values for

periods of ~ 0.5 years, eventually returning to just above the upper boundary by the end of the sample. Both Tooth #06 and #09 generally increase in value outside of the local range as time progresses, although Tooth #06 is more consistency in the degree of rise and fall.

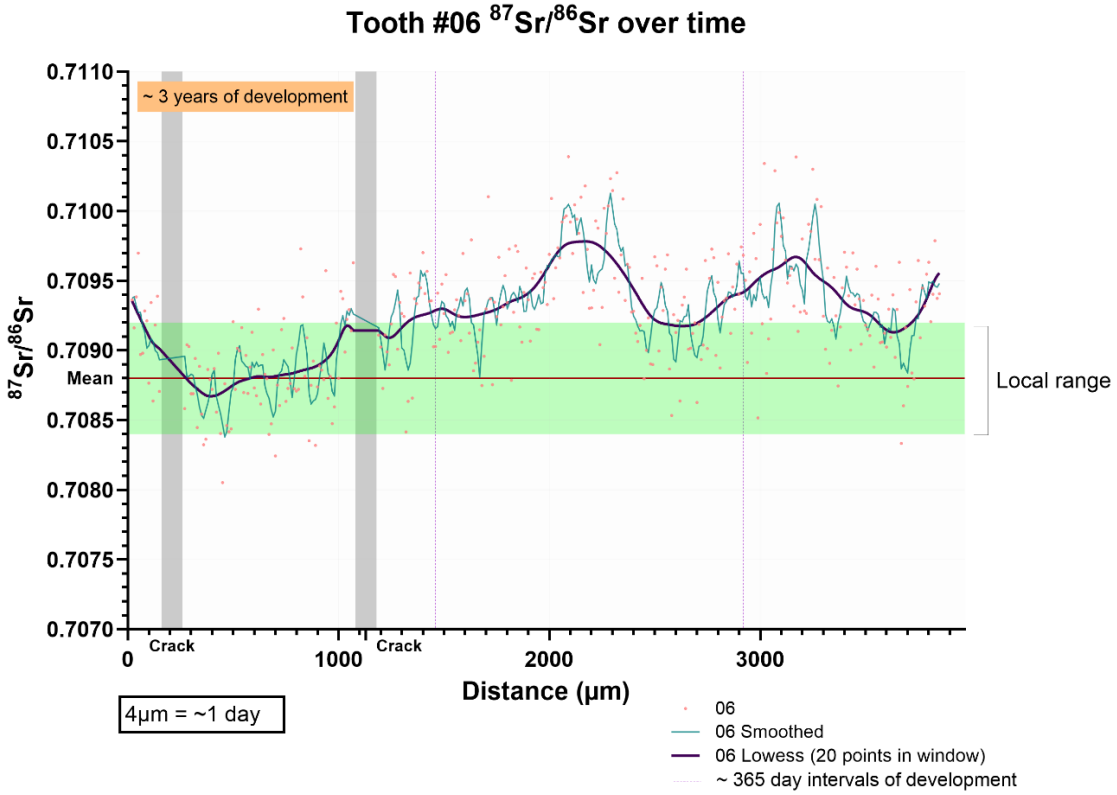


Figure 24. Timeseries plot of Tooth #06 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (06), 2nd order smoothing for short term trends (06 Smoothed), and fine averaging for long term trend representation (06 Lowess).

Tooth #09 represents approximately 3 years of development, with the latter two years spent climbing in value toward the end of the sample, although there is interaction with the upper margin of the bioavailable range for approximately 1 year.

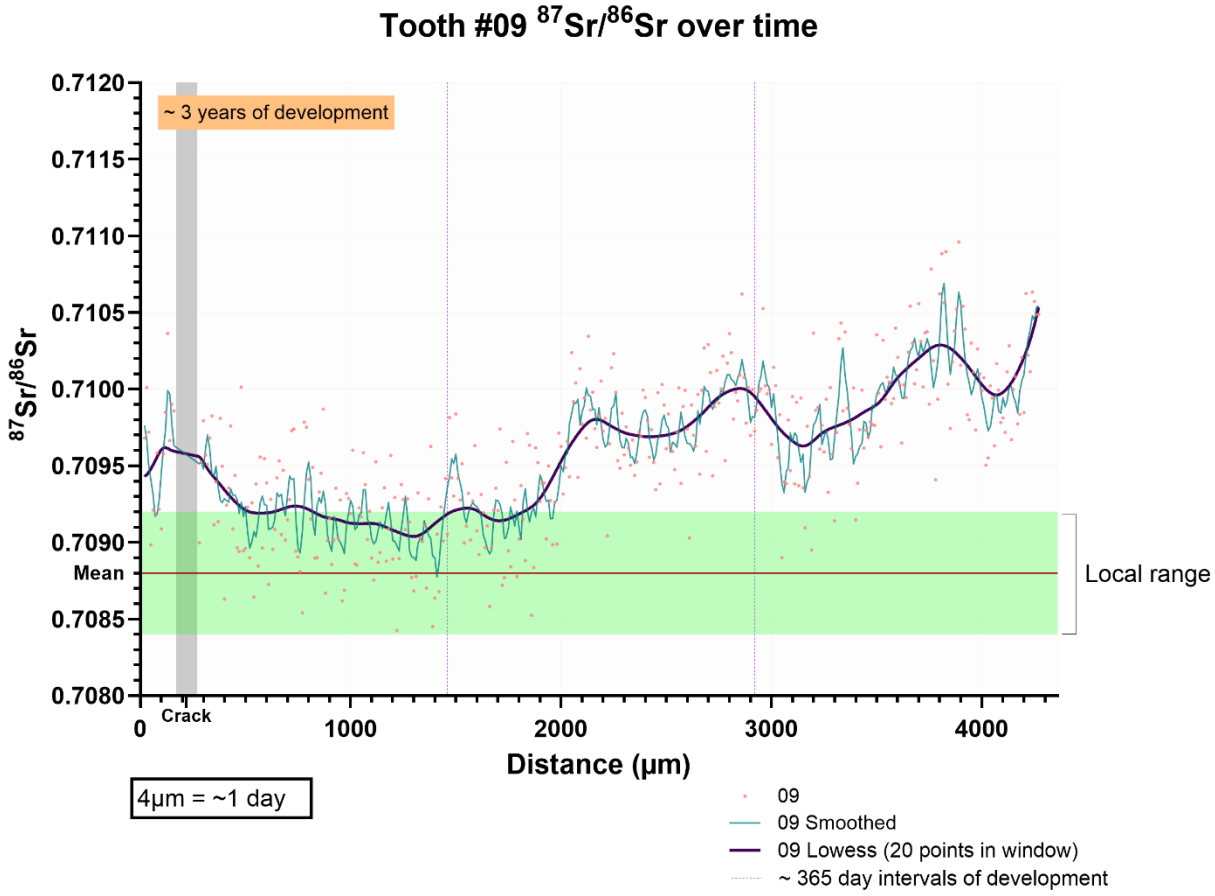


Figure 25. Timeseries plot of Tooth #09 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (09), 2nd order smoothing for short term trends (09 Smoothed), and fine averaging for long term trend representation (09 Lowess).

Tooth #08 (Figure 26) initially dropped in value steadily until a large spike into the local range between ~ 1000µm and ~ 1500µm. After falling briefly, after ~ 2000µm the moving averages begin to trend upward gradually over the rest of the growth period. While fluctuations do occur, they seem to return to the upward trend after any drop periods in both the short- and long-term moving averages, often lasting <0.5 years with the long-term average. By the end of the sample the individual points and both short- and long-term moving averages begin to

periodically enter the local range, with final values as the development period approaches the terminal end trending increasingly toward and into the lower portion of the local range.

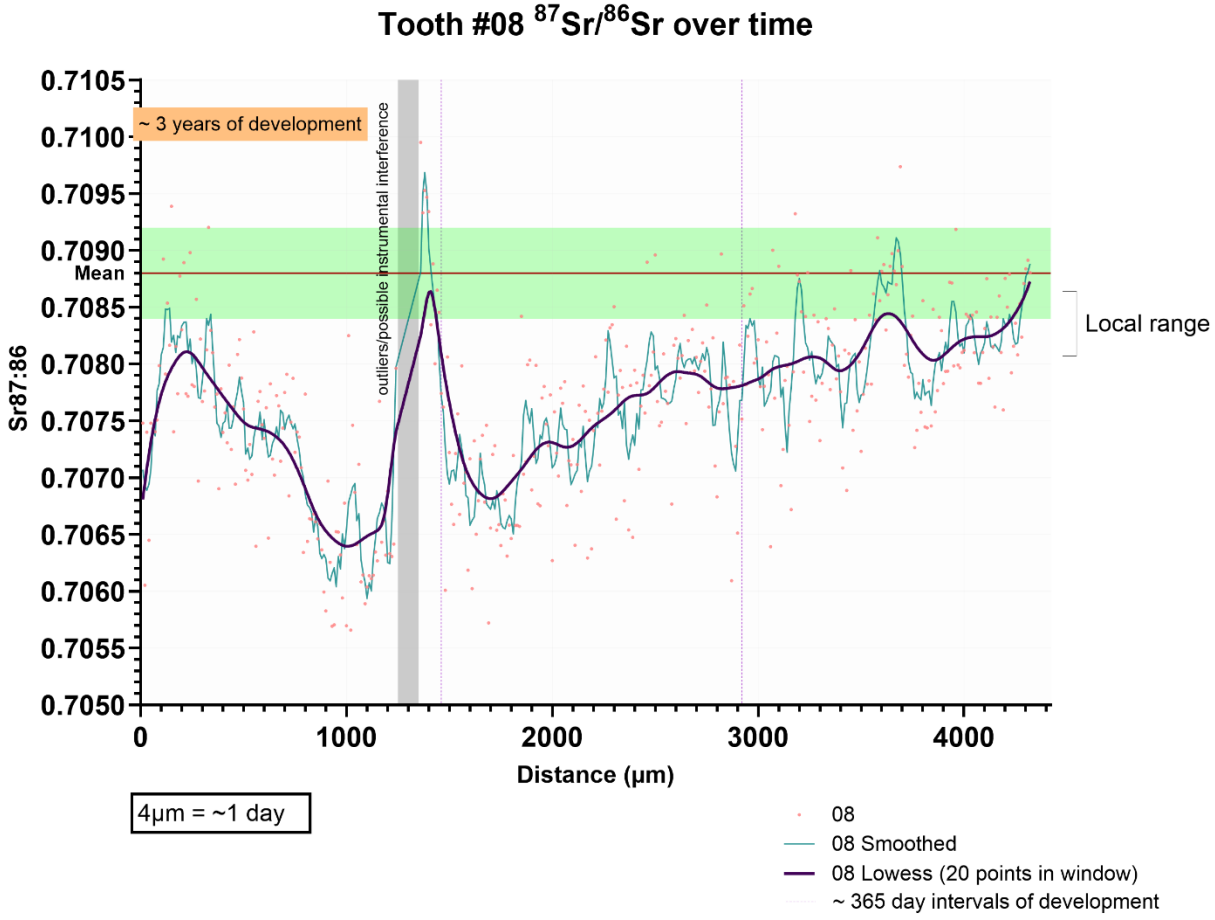


Figure 26. Timeseries plot of Tooth #08 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (08), 2nd order smoothing for short term trends (08 Smoothed), and fine averaging for long term trend representation (08 Lowess).

Tooth #11 (Figure 27) also represents approximately three years of the growth period, and initially shows a reduction in $^{87}Sr/^{86}Sr$ ratio values with a gradual incline toward the local range.

Again, this sample has more consistent periods of year over year fluctuations, but they all occur outside the local range.

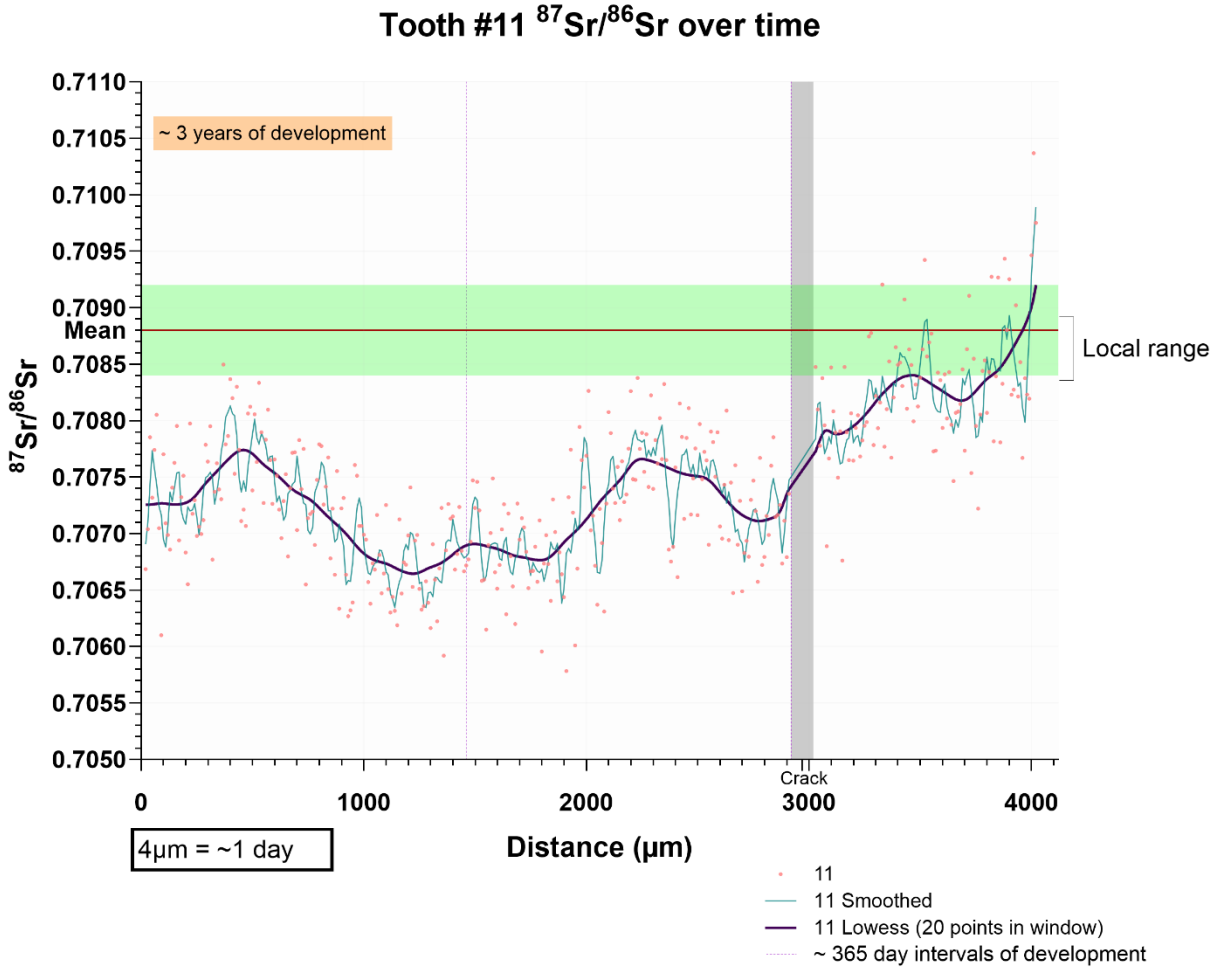


Figure 27. Timeseries plot of Tooth #11 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (11), 2nd order smoothing for short term trends (11 Smoothed), and fine averaging for long term trend representation (11 Lowess).

In the case of all non-local individuals as a whole, the samples vary individually with regard to the concentration of the majority of points either below or above the outer bounds of the local range. Both Tooth #06 and #09 trend toward values greater than the upper bound of the local region, while #08 and #11 trend toward the lower bound of the local region.

4.5 Third molars

Table 8. Information table for third molar samples and results

Tooth #	***Tooth type***	***95% Confidence interval***	***Standard error of mean***	***Locality***	***Development period of tooth type***	***Development period represented***
12	ULM3	0.7093 – 0.7093	1.488e-005	Primarily non-local	~8 – 11 years	~ 3 years
13	ULM3	0.7076 – 0.7078	4.265e-005	Primarily non-local	~8 – 11 years	~ 2 years
14	ULM3	0.7072 - 0.7074	3.846e-005	Primarily non-local	~8 – 11 years	~ 3 years
15	ULM3	0.7091 – 0.7092	1.925e-005	Variable locality	~8 – 11 years	~ 3 years
17	ULM3	0.7089 – 0.7092	2.052e-005	Primarily local	~8 – 11 years	~ 3 years
19	LLM3	0.7090 – 0.7090	1.638e-005	Primarily local	~8 – 11 years	~ 2 years
21	URM3	0.7091 - 0.7092	1.917e-005	Variable locality	~8 – 11 years	~ 2 years
22	URM3	0.7086 - 0.7087	1.599e-005	Primarily local	~8 – 11 years	~ 3 years
23	ULM3	0.7090 - 0.7090	1.639e-005	Primarily local	~8 – 11 years	~ 2 years

Of the third molars analyzed (Table 8), four were designated primarily local: #17, #19, #22, #23; three primarily non-local: #12, #13, #14; and two variable locality: #15, #21. The total

developmental period for third molars is more variable than other teeth, but typically begins at approximately 8 years of age with maturation of the crown complete by ~ 11 years of age.

5.5.1 Local

Upward trending short- and long-term moving averages were observed in the data of Tooth #17 (Figure 28), representing ~ 3 years of the development period. At around 1500µm, the moving averages steadily begin an upward trend at ~ 2000µm, which crosses the upper bounds of the local region at ~ 3000µm before returning to the local zone after about a year of non-local ratios. At the point where the long-term moving average leaves the local range there is some indication of consistent periods, however these averages do not directly cross into or out of the local range and therefore conclusions cannot be made as to the nature of this movement.

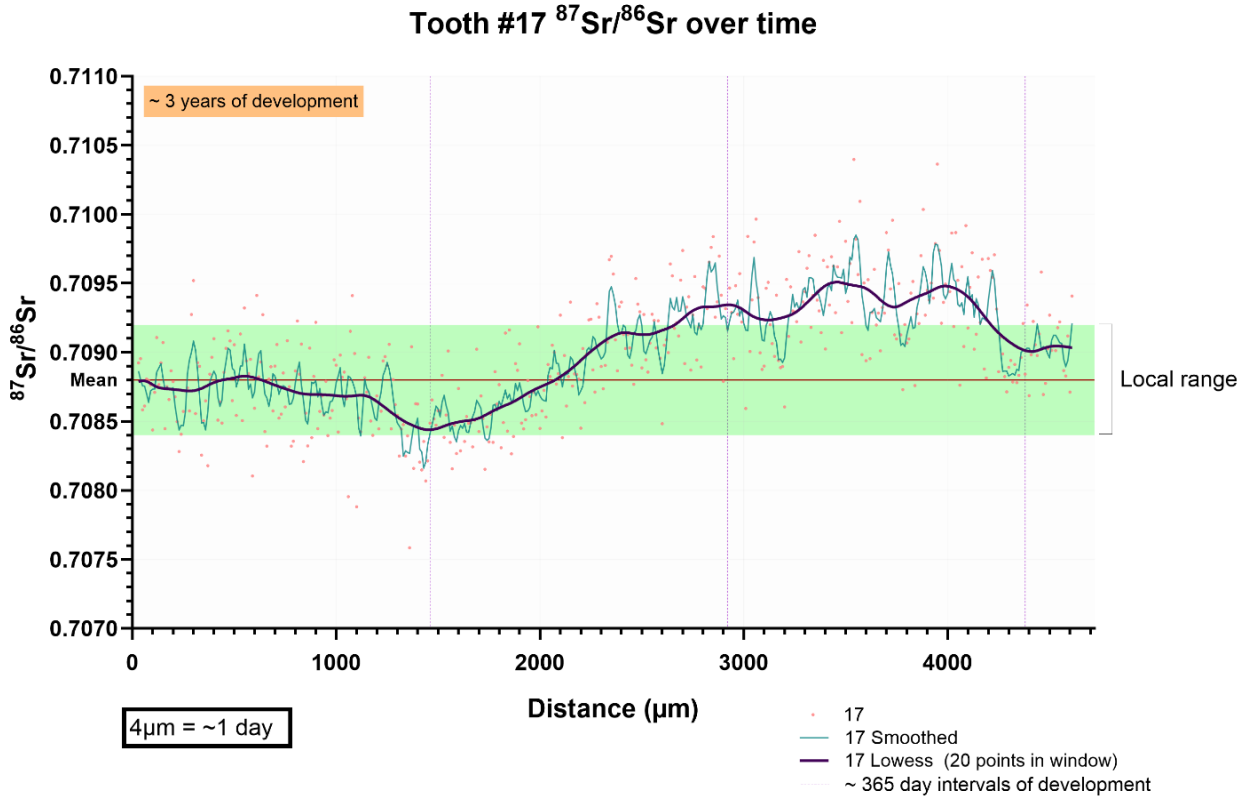


Figure 28. Timeseries plot of Tooth #17 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (17), 2nd order smoothing for short term trends (17 Smoothed), and fine averaging for long term trend representation (17 Lowess).

Tooth #19 (Figure 29) represents approximately 3 years of development and initially trends downward from just outside of the non-local region before stabilizing within the upper bounds of the local range. Some periods of fluctuation do occur, particularly in the period up to ~ 2000µm the values trend toward the upper bound of the local region before briefly crossing it, however

the timing of each fluctuation is not consistent. Following this benchmark the values seem to stabilize more consistently in the upper portion of local range.

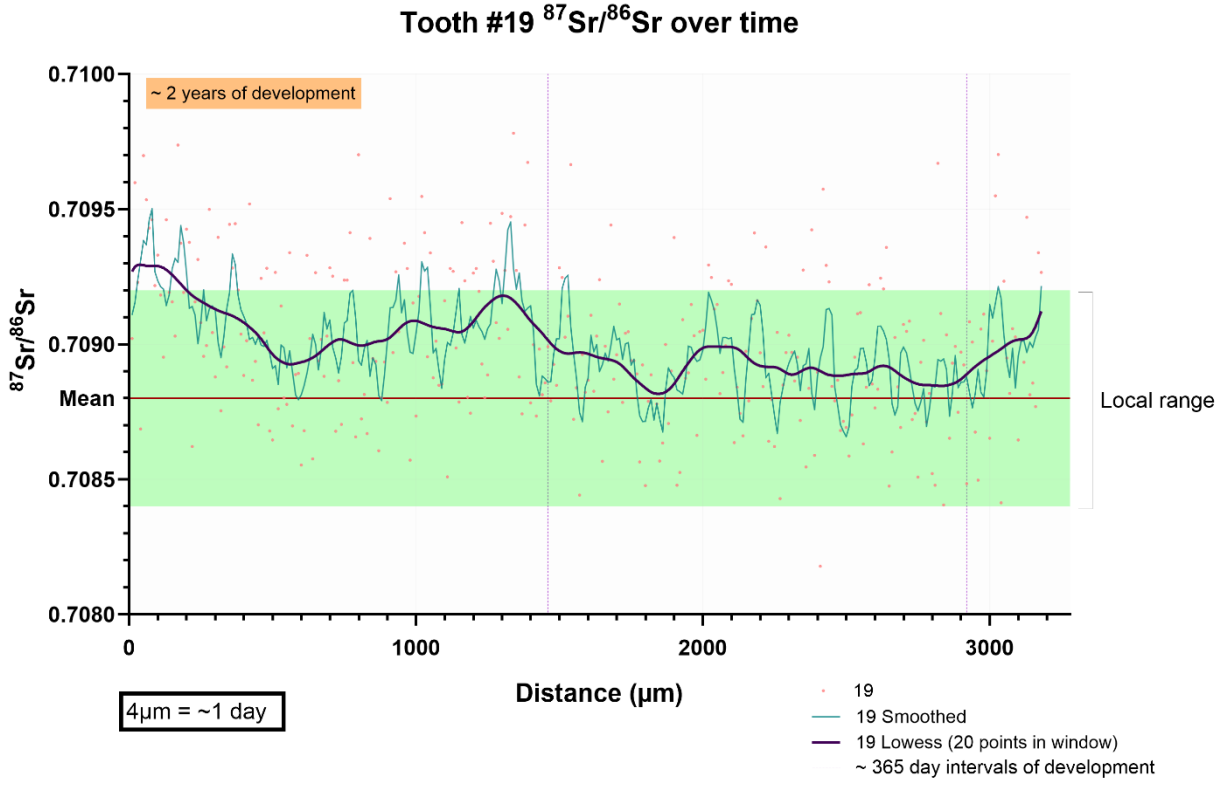


Figure 29. Timeseries plot of Tooth #19 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (19), 2nd order smoothing for short term trends (19 Smoothed), and fine averaging for long term trend representation (19 Lowess).

Tooth #22 (Figure 30) has a more subtle upward trend toward the local mean in comparison to Tooth #19. This trend is sustained through to the end of the growth period is representative of approximately 3 years of development. The long-term moving average remains in the local range for the entire growth period, with short drops of the short-term average

dropping infrequently below the local range. Despite this, ~30% of the total data points fall outside of the local range, with most of the points falling below the lower local boundary. As the long- and short-term averages meet the mean of the local boundary the raw data range is mostly settled within the local range, with a minority extending beyond the upper local boundary.

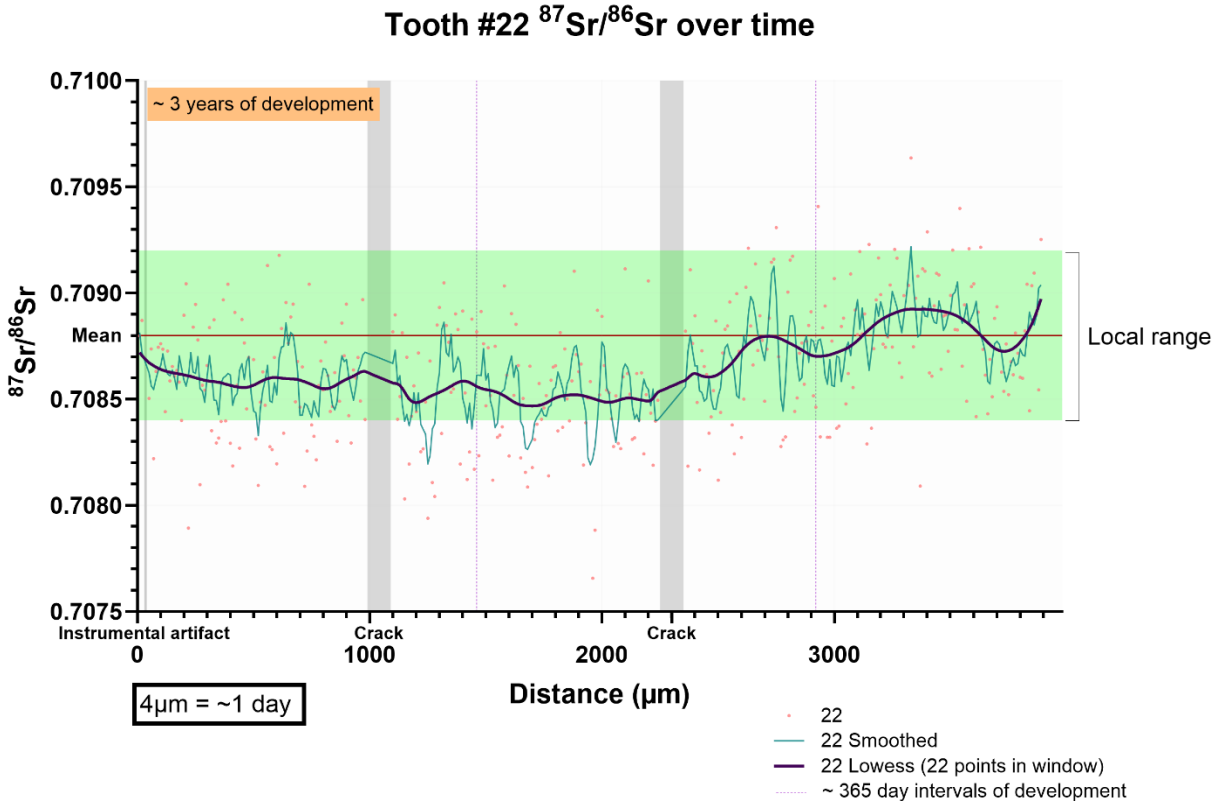


Figure 30. Timeseries plot of Tooth #22 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (22), 2nd order smoothing for short term trends (22 Smoothed), and fine averaging for long term trend representation (22 Lowess).

4.5.2 Non-local

In contrast to the primarily local samples, these teeth do not share any clearly identifiable trend in common aside from their non-local designation. Tooth 13 (Figure 31) represents approximately 2 years of development, and initially trends upward toward the lower bound of the local range, following a relatively stable trajectory. The values cross the lower bound of the local range briefly after about a year of development, before trending downward and out of the local range again with the end of the developmental period returning to around 0.7070 with no indication of deviation from this downward trend.

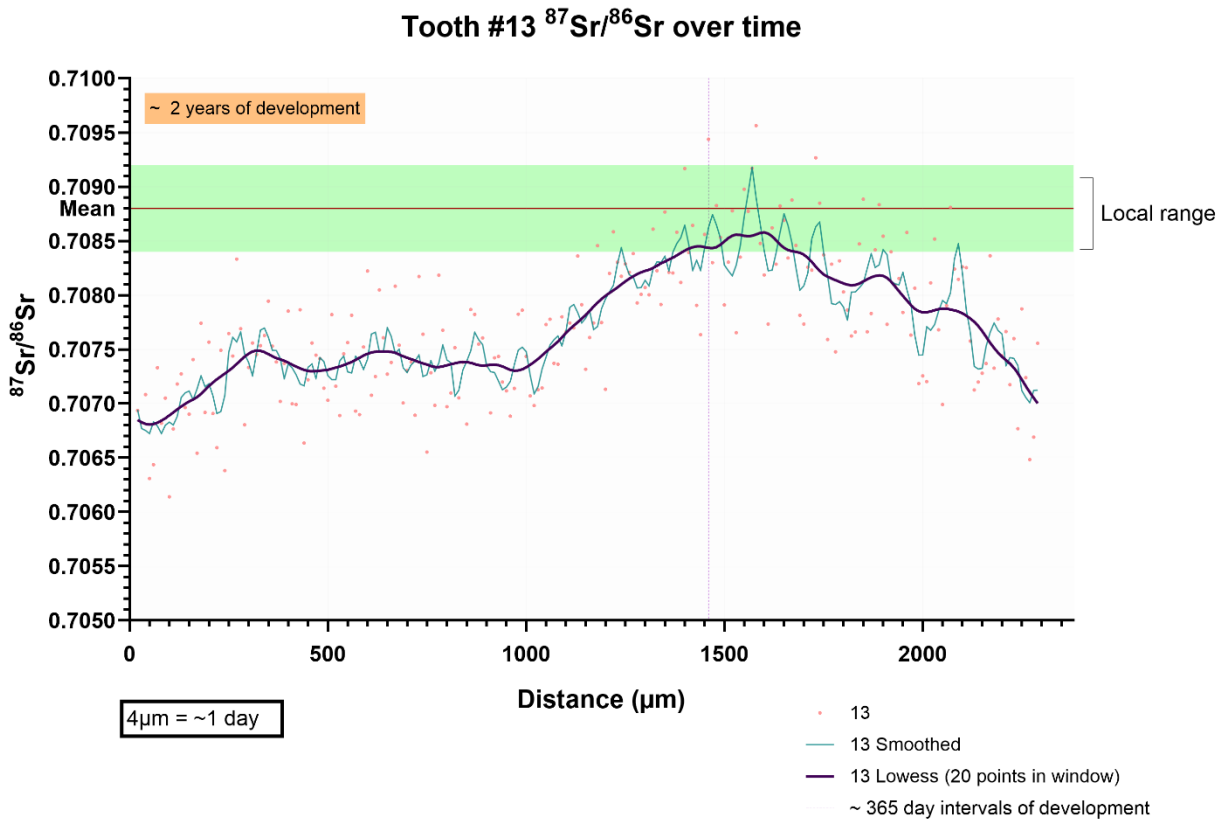


Figure 31. Timeseries plot of Tooth #13 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (13), 2nd order smoothing for short term trends (13 Smoothed), and fine averaging for long term trend representation (13 Lowess).

In contrast, tooth #12 (Figure 32) represents approximately three years of development and largely stays above the upper bounds of the local range. However, this tooth also does cross into the local region multiple times at roughly equal intervals of between half, and three quarters of a year. While the data is not conclusive and does not reach the local region for long periods (rather it seems to be a punctuated drop) it could possibly indicate a consistent pattern of movement which relates to the local range.

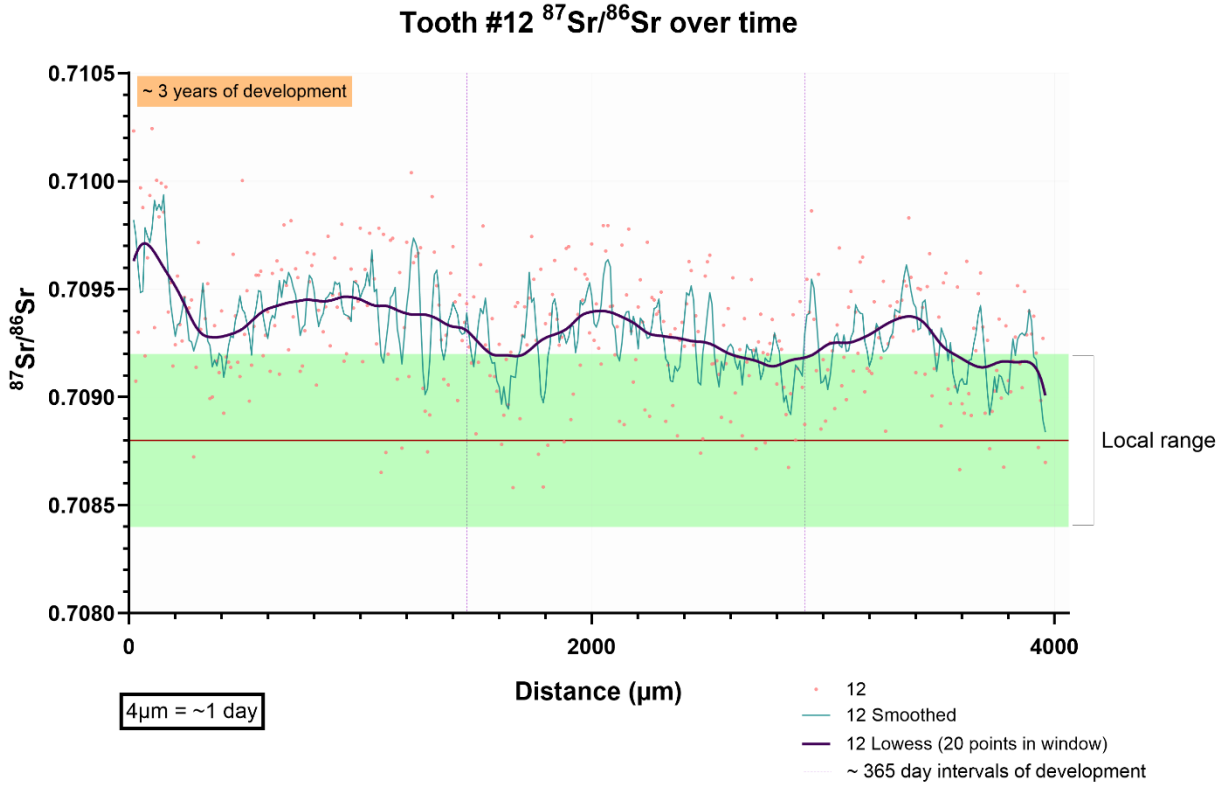


Figure 32. Timeseries plot of Tooth #12 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (12), 2nd order smoothing for short term trends (12 Smoothed), and fine averaging for long term trend representation (12 Lowess).

Tooth #14 (Figure 33) stays almost entirely below the lower boundary of the local range, with brief periods of points entering the range each year. However, both the short-term and long-term moving averages remain below the local range. In the three-year period of development represented, the data fluctuates over the year with four identifiable periods of rise and fall, each around one half to one third of a year in length. This is perhaps the clearestrepresentation of potential identifiable patterns of movement outside of the local range in this dataset, while Tooth #12 shows the most clearly identifiable pattern of mobility with movement to and from the local region.

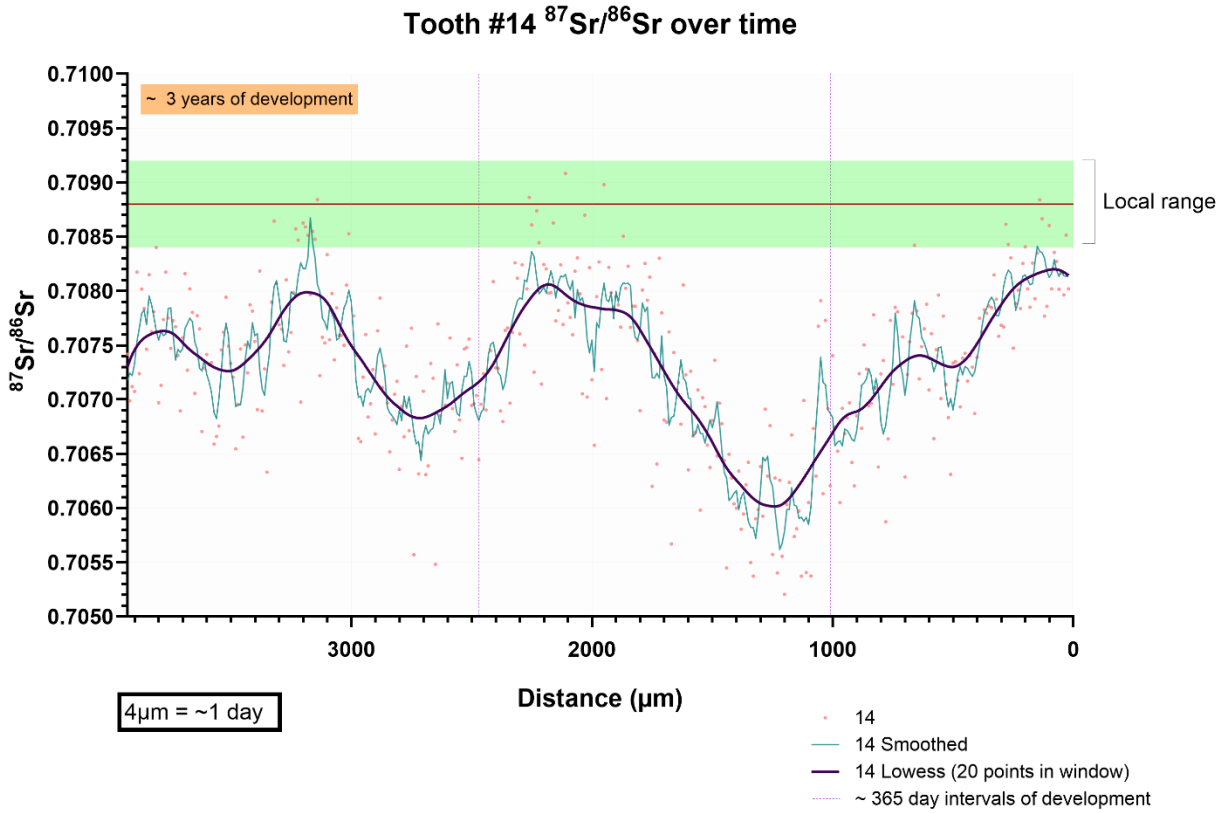


Figure 33. Timeseries plot of Tooth #14 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (14), 2nd order smoothing for short term trends (14 Smoothed), and fine averaging for long term trend representation (14 Lowess).

Finally, both Tooth #15 (Figure 34) and Tooth #21 (Figure 35) are identified as having variable locality, however Tooth #15 represents approximately three years of development and appears to largely stay within the local range prior to an upturn in values at the beginning of the ~10 year period, possibly due to the wide distribution of data points within and outside of the local range.

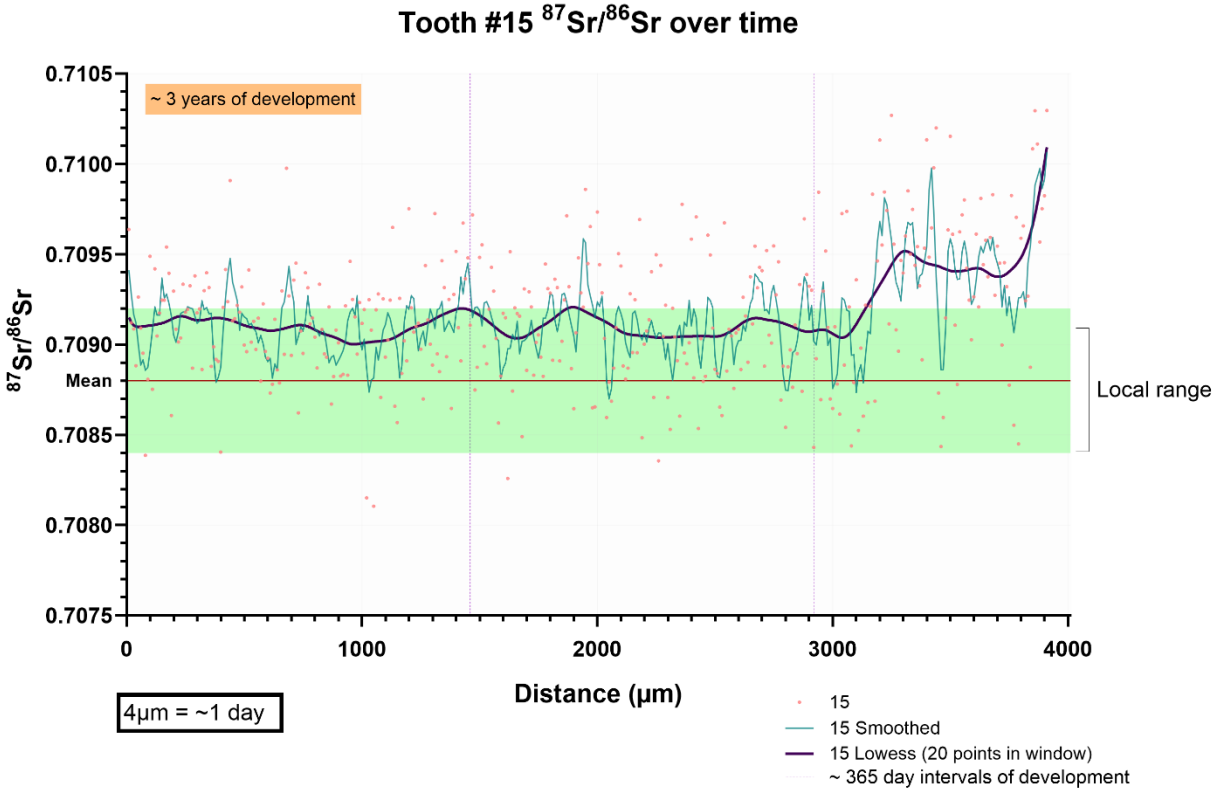


Figure 34. Timeseries plot of Tooth #15 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (15), 2nd order smoothing for short term trends (15 Smoothed), and fine averaging for long term trend representation (15 Lowess).

Tooth #21 (Figure 35) represents approximately two years of the developmental period and appears to be a more typical presentation of variable movement, with identifiable periods of movement to and from the local range. The initial, largely non-local, gradually declining moving average moves into the local range over the course of approximately three-quarters of a year. The next indication of non-local mobility occurs around one year later, and the data terminates in the upper bounds of the local range. This is one of the few examples of an identifiable and

temporally restricted pattern of mobility to and from the local range, although this would only be fully confirmed with more of a development period represented as a result of the minimal variation outside of the local range which *could* indicate some other variation within the local range.

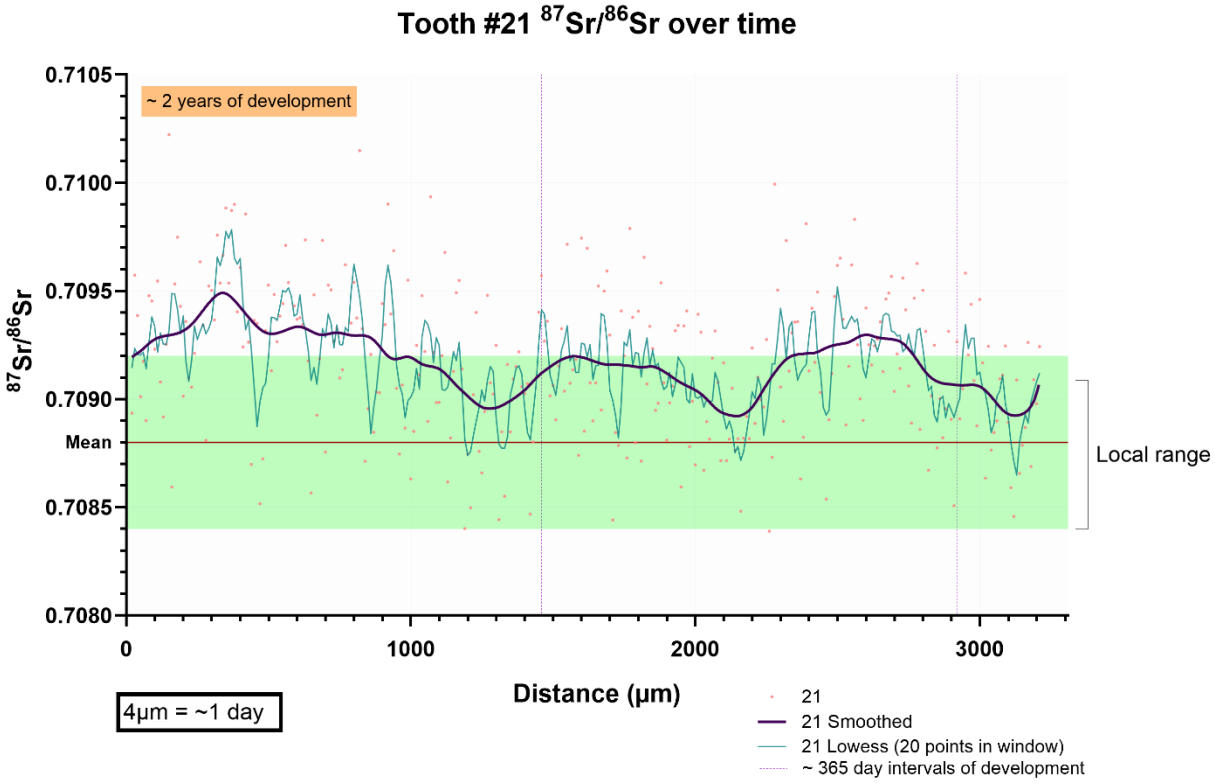


Figure 35. Timeseries plot of Tooth #21 ratios with approximate age landmarks, local bioavailable mean, and local bioavailable range. Includes exact spot ratio data (21), 2nd order smoothing for short term trends (21 Smoothed), and fine averaging for long term trend representation (21 Lowess).

Chapter 5: Discussion

5.1.1 Local and non-local mobility

Initial hypotheses for this study indicated that some level of mobility outside of the local area was expected based on the inconsistent levels of trace element exposure found in previous studies (Ruddell, 2025; Tan, 2021), as well as archaeological evidence of at least some level of trade evidenced the presence of an imported pot found on the site. However, the degree to which variability during all periods of tooth development studied here was not expected and seems to reflect the variability in the ways that individuals proceeded through early childhood and adolescence as opposed to following one pattern of movement at certain periods of their lives. Of course, an important consideration in the variability of these data is that the local area is defined and perceived through a modern perspective, which may not align with the perspectives of the individuals from the EB 1B (Gregoricka, 2021). Notably, the way that locality is interpreted in this study is restricted from working within the parameters of personal identity and individual perceptions of local and non-local boundaries due to the type of contextual information available to us. That is to say that this site's prehistoric context prohibits researchers from concretely deciding what is non-local beyond the bounds presented by bioavailable sample data. As such, this discussion does not attempt to work through the identities of these individuals. Instead, this discussion grapples with how embodiment of physical mobility may clarify the perceived versus actual expectations of social organization as presented in previous studies, as well as the challenges associated with identifying mobility using Sr ratio analysis.

5.2.1 Social organization

As established above, this study is unlikely to be able to define the complexity of mobility at WF100 in this study. It does, however, clarify (and complicate) some of the assumptions held about lack of mobility being an indication of social complexity and urban sedentarism at the site (Barker et al., 2007; Philip, 2008)). The premolars data (Figure 36) ranges in patterns from non-local to local, and with varying lengths of time spent in the local range, however each tooth (aside from Tooth #24) leaves the local range between ~1 and 2 years of age before diversifying.

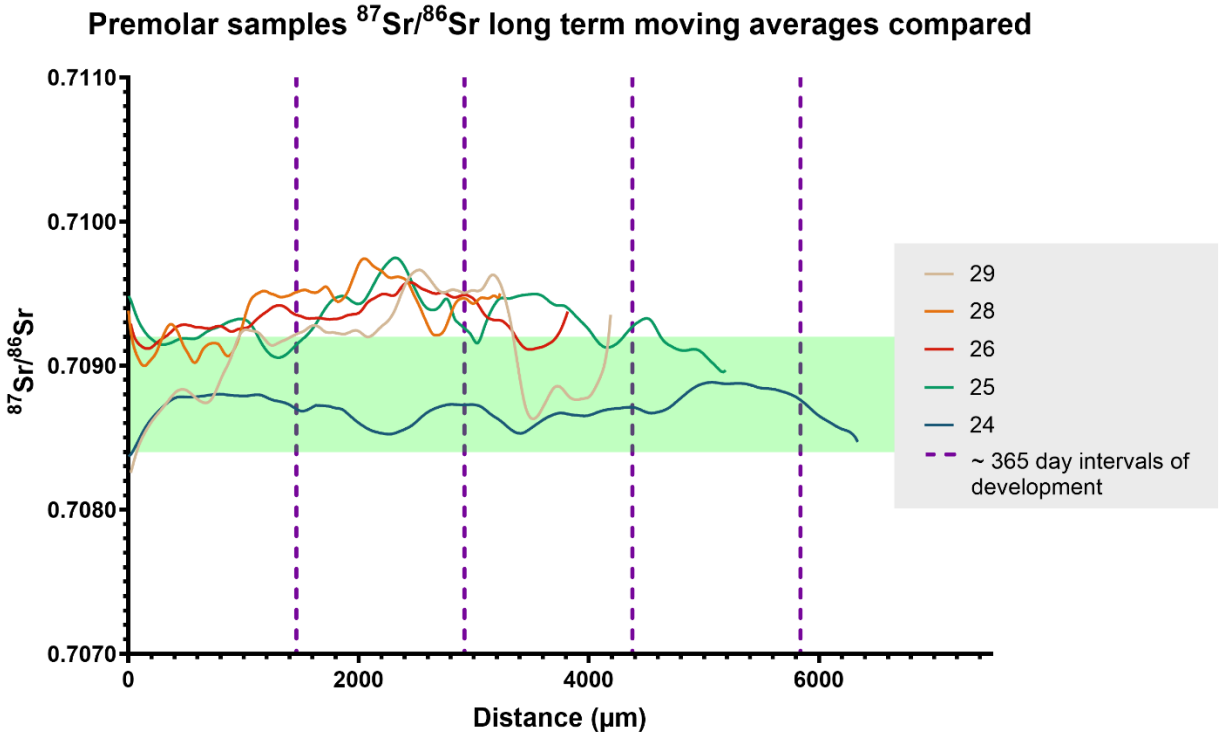


Figure 36. Comparison of all long-term moving averages (Lowess) of all premolar samples with approximate ages

While most of these teeth begin to trend back toward the local range after approximately two years of development, the degree to which they maintain this trend-- or, in the case of Tooth #28, follow it at all-- is not consistent. Due to the small sample size this is not entirely surprising, but the overall variation in patterns year over year seems to indicate that most of these individuals were likely local or interacted with the local area, and then around one year began to move out of the local area. After the two year mark the interaction of the values with the local area varies, suggesting perhaps intermittent movement in to and out of the area, or they could have been receiving food stuffs from the local area, though this would have to be fairly significant to result in the changes we observed here, and trade at this scale is not evident at the site. Considering the time scale of the movement fluctuations – sometimes over half a year – the scale of food storage and production at the sites which they go to outside of the local area would be a relevant consideration. However, this level of between-site and temporally specific comparative analysis has not, to our knowledge, been conducted at a scale which would be valuable for our purposes. However, this concept of returning to place has been put forward in the context of secondary burial at Bab edh Dhra in between periods of non-local occupations (Chesson, 2023) and *could* be an avenue for future research with regard to WF100. In contrast, Tooth #24 appears to have developed entirely locally, suggesting possibly a temporal separation between this and the other premolars with regards to social organization or a more diverse collection of mobility practices at this site.

The possibility of this temporal or social organization division between individuals at this site are also supported by the incisors (Figure 37) which represent a similar time period and also demonstrate two clearly opposed mobility types. One is initially very non-local and after a few

years of development enters the local range, while the other is almost entirely local for the two years of development that it represents.

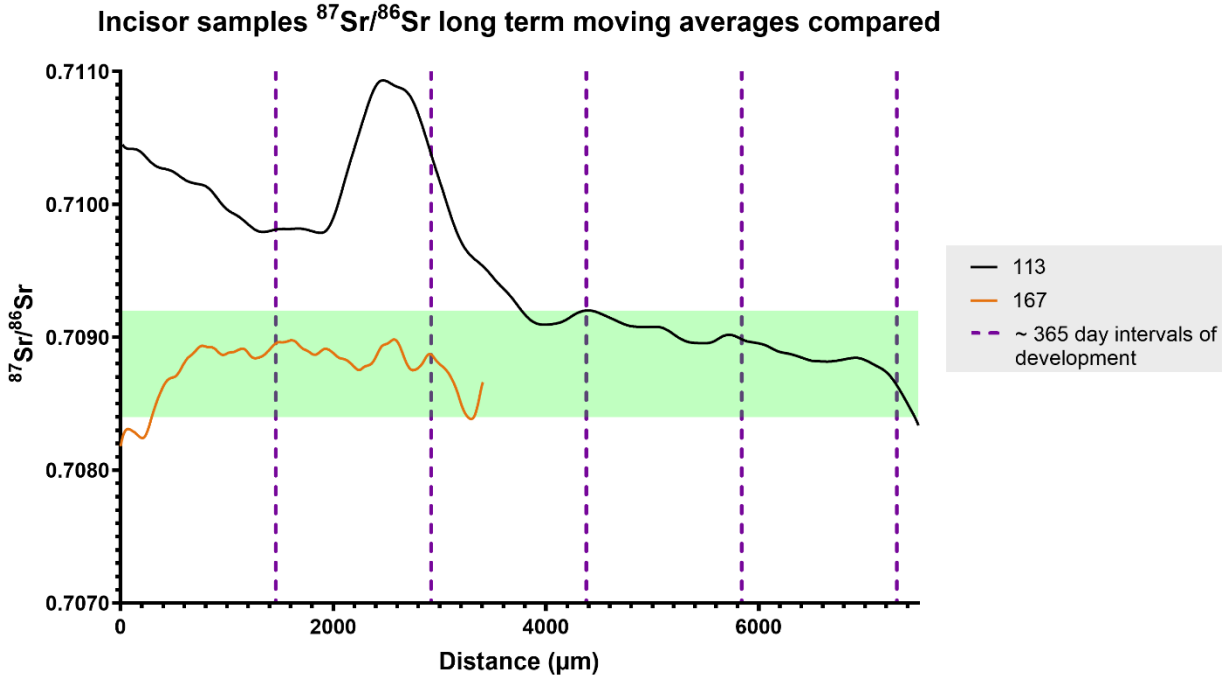


Figure 37. Comparison of all long-term moving averages (Lowess) of all incisor samples with approximate ages

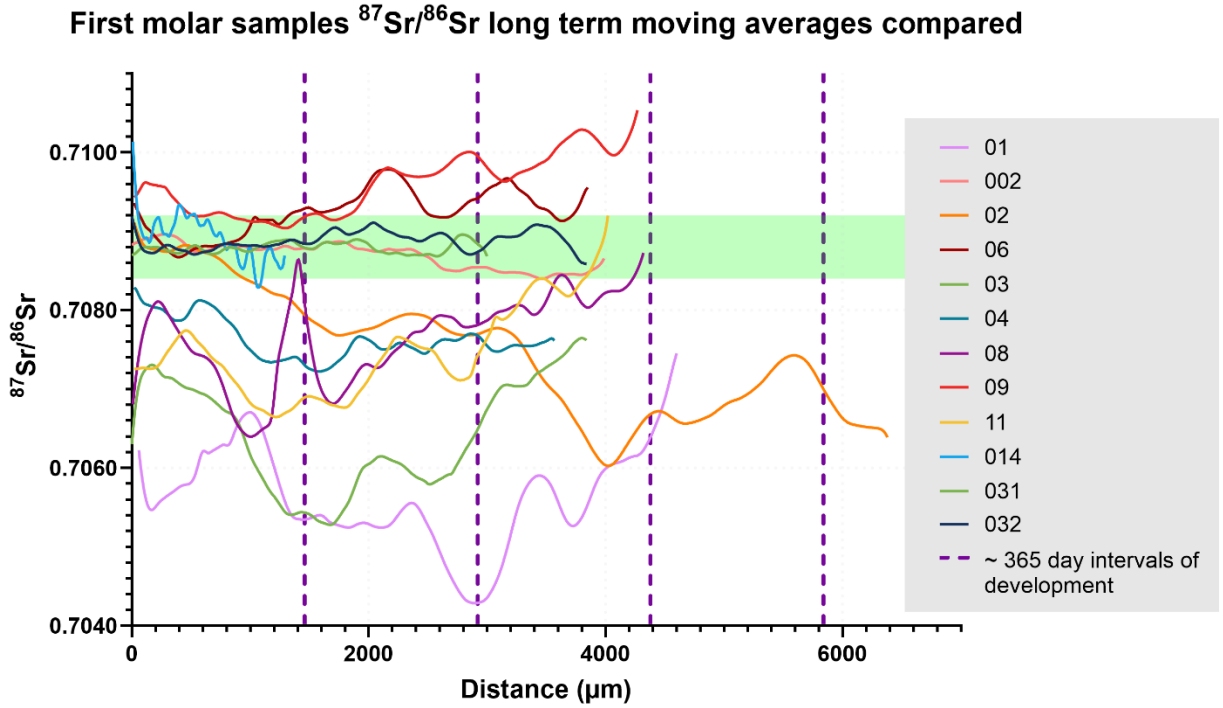


Figure 38. Comparison of all long term moving averages (Lowess) of all first molar samples with approximate ages

In the first molars (Figure 38) this diversity is perhaps even more pronounced with only 4 samples (Teeth #032, #002, #031, and #032) showing a fairly consistent and stable continuing trend within the local range. Aside from this, there are few opportunities to identify a temporally restricted trend across the samples. Though some, for example Tooth #11 and Tooth #08, are similar in values and trends, the small sample size does not allow for a clear identification of a trend. Beyond this, there is no clear interaction relationship with regard to the local area across individuals in which clear, temporally restricted, periods of local/non-local movement patterns have been indicated. Instead, a wide variety of locality and movement patterns are observed.

As children enter later periods of development, such as demonstrated by the 3rd molars (8-11 years), there does seem to be a slightly less variability in movement into and out of the

local area as well as overall diversity in the patterns of movement seen across samples (Figure 39)

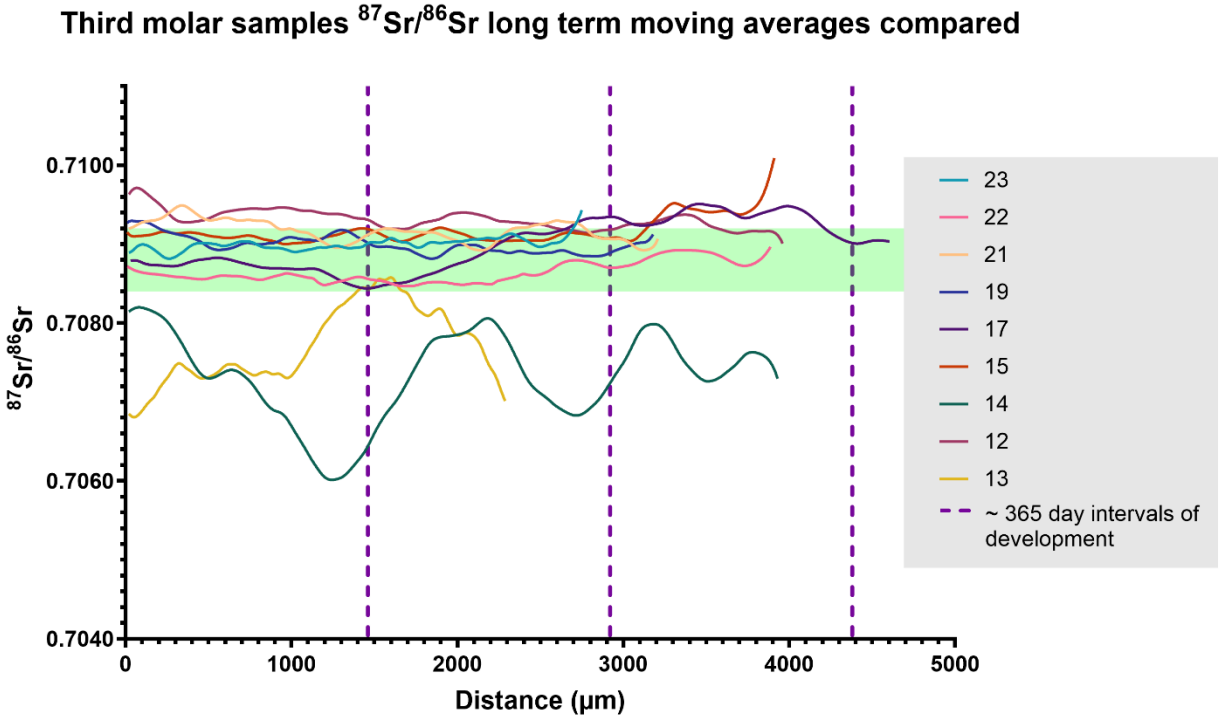


Figure 39. Comparisons of long-term moving averages (Lowess) for all Third molar samples with approximate ages.

While the actual age of development for third molars is highly variable, we can still understand this data as representative of late childhood to early adolescence on average. These samples seem to demonstrate that most of these children were at least more consistently local or non-local, with many average trends situated primarily in the upper half of the local range during the developmental period. As these data progress past ~ 3000µm (where it was possible to place a laser line that was this long) these trends seem to diversify again, with individuals moving out of or into the local area during this period, perhaps suggesting some age specific constraints on

mobility at this age. However, two individuals (tooth #13 and #14) both vary widely in overall trend patterns, and only #13 seems to reside briefly in the local area for less than a year, suggesting a difference in these individuals compared to the rest of the dataset. While these could be the result of nomadism, it could also be suggested that migration from another community would result in these values as different and identity specific reasons for mobility.

In relation to the original questions which guided this study, these results seem to emphasize the importance of Nicolle's (2023) encouragement of a regionally specific approach to investigation with special emphasis placed on the aspect of choice which echoes other authors discussions of mobility as embodied aspects of individual, local, and community identity (Agarwal, 2016; Gregoricka, 2021; Lock & Nguyen, 2010). The two main categories of mobility: local and non-local, require us to assume two things in the development of a universal hypothesis. First is that the local range is representative of what individuals regarded as 'local', and second is that the reason for mobility (or lack thereof) is uniform across individuals and the time periods they each lived in (Gregoricka, 2021). However, it would be disingenuous as an anthropologist to apply these assumptions universally, as they disregard the individual embodied experiences, contexts, and choices of past communities and individuals in their relationship with the environment (Gregoricka, 2021; Lock & Nguyen, 2010; Tilley & Cameron-Daum, 2017). The results of this study broadly emphasize the importance of these approaches given the diversity in locality types and patterns at any given age period. Furthermore, there is little evidence for one dominant pattern of mobility in this community.

Certainly, some individuals have similar patterns of mobility, however, many also differ in their overall trend and physical relationship to the local area. This suggests that individuals likely differed, particularly in early childhood in the permanency of the local area, possibly

becoming more local with some non-local movement depending on the individual as they reached early adolescence. Considering it is known that role specialization was occurring at WF100, one hypothesis for the reason for this may be that children began to specialize into a diverse array of roles in the broader community, including pastoralism. This would be supported by modern ethnographic evidence and the more recent 19th and 20th century material evidence of Bedouin communities which suggest that the developmental period of the third molars aligns well with the social benchmark in which children begin to participate in long distance herding on their own (Mithen, Finlayson, et al., 2025; Palmer et al., 2007). Furthermore, other sites in the Wadi Faynan region known to have been used by these Bedouin communities show evidence of long-term occupation, and re-occupation of sites which may indicate that the longer periods of non-local movement may be indicative of a similar pattern of mobility. In particular, these communities have been described as following a variety of seasonal patterns which vary widely from each other, noting that homes typically are reserved for the winter months or storage while certain communities would remain in tents for the full year, continually moving throughout the landscape, while others followed stricter seasonal rotations. Ultimately this is to say that there is, even today, different ways of living on this landscape in the form of modern pastoralism, and WF100 seems to be in support of the possibility of these diverse yet co-existing pastoral patterns and choices. This would also align with the possible site use specifically for storage or cemeteries throughout the broader Levant such as seen at Bab edh Dhra (Chesson, 2023; Nicolle, 2023). However, until further evidence of this is uncovered this will remain a hypothetical in the context of this study, though this evidence of this variation does begin to elucidate some of the variabilities researchers have observed at WF100, which have appeared to be inconsistent from the broader historical interpretation of lifeways in the Levant.

5.3.1 Challenges of using sequential Sr analysis in Jordan

As we do not have the isotopic data relevant to the wider Jordan region that aligns with the ranges of our study's results, this leaves many questions open as to the distances being travelled as well as the diversity of isotopic values found in the southern Levant. While Wang et al.'s (2023) map of bioavailable strontium, also presented in Al Shorman (2025), provides a preliminary map of values which would have contributed to the Southern Jordan region, the portion of Wadi Faynan in which WF100 is located is not thoroughly identified and the areas which are associated with $^{87}Sr:^{86}Sr$ ratios span over 100km of land from south of Petra to Jericho. The values which are designated for the geological regions which form portions of the Wadi Faynan landscape span from 0.707710 – 0.709260, which does not align with the full range of $^{87}Sr:^{86}Sr$ ratios presented here, and only barely encompass the local range identified for WF100. While these studies present a place to start in identifying movement throughout the Jordan landscape, their lack of biologically derived Sr ratios for identifying these regions and preference for identification based on the geological contents of the landscape negate the influence of fractionation on bioavailable Sr values.

Both Holt et al (2021b) and Wu et al (2024) identify the significance of homogenization of Sr ratios due to environmental cycling and the many different sources of Sr isotopes in the broader environment. With water being identified as a significant factor in these evaluations, the climate circumstances at WF100 become especially relevant regarding isotopic ratios at the site and the broader Levant. The significantly more moist environment associated with frequent flooding events is both in opposition of today's desertified landscape, and also relevant to the

variation in bioavailable Sr as a result of fractionation. Differences in climactic conditions may have affected the source of water in the environment, seasonal differences, and the vegetation available for consumption that would have be growing in the area at the time (Holt et al., 2021a; Wu et al., 2024). As different plants uptake Sr from different water sources (some from the surface and some from the ground water) the weather events such as flooding and rainfall which were taking place would have affected the fractionation of values through these plants, as well as the overall values of ground water and surface precipitation as the water table is effected and erosion occurs during periods of precipitation. This results in a temporally and regionally specific bioavailable isoscape for the region, which should be taken into account when considering the effectiveness of geological Sr values for observing mobility which relies on human consumption of living organisms.

Ultimately, these areas of limited context prohibit the use of currently available Sr maps to track movement across the landscape and limit this study to the use of local versus non-local narratives of analysis. However, the more novel aspect of this study takes advantage of the use of LA-MC-ICP-MS in the way it can be employed as a method for understanding temporospatial movement especially in pre-historic communities. Sequential sampling of dental enamel using LA-MC-ICP-MS does not appear to be a common method for observing locality in Jordan, or even more broadly in the bioarchaeological discipline. Typically, many studies including those using LA-MC-ICP-MS or some variation of ICP-MS employ the use of bulk sampling to identify local individuals (see (Al-Shorman et al., 2025; Ingman et al., 2021; Kramer et al., 2021; Perry et al., 2008, 2009) however, I argue that this study demonstrates the homogenization that occurs with regard to locality when this approach is used.

In Chapter 4, the 95% confidence interval was used to identify whether the individual was a primarily local or non-local individual during the period of the tooths development. However, many of these teeth demonstrated mobility which was in opposition to their designation. Many teeth which were designated primarily local demonstrated extended periods of movement, while variable individuals showed remarkably stable locality with only one large portion of movement which effectively skewed the confidence interval and mean of these samples. Furthermore, the variation and range in values differed widely in some samples, indicating that additional testing should be completed to more completely understand these datasets. This indicates that bulk allocations of individuals to a local or non-local designation may homogenize long temporal development periods which then skew the overall mean toward these longer periods of sedentarism. This is particularly relevant to samples which may have multiple periods of mobility which may average to a local value but actually represent many periods of non-local movement.

Furthermore, in current studies which do employ sequential sampling using LA-MC-ICP-MS, there is not a clear agreement on how to define a local range. While much of the Sr analysis in Jordan, particularly in the Wadi Faynan region, have defined the local range of values as the limits of the 95% confidence interval of the mean (Perry, 2012; Perry et al., 2008) other authors may employ simply the overall range of values provided by the bioavailability samples (see Wathen-Avila et al., 2025). This may lead to further confusion and a lack of cohesive trust in the reliability of future Sr studies. In the case of this study, two major issues of concern were identified, one being the appropriateness of using the confidence interval of the mean for the bioavailable range as determined by the faunal data. Unfortunately, in this study only a small number of faunal samples were analysed (n=11) however, this is not necessarily out of the norm

for other studies in the region, which often sample less than 20 samples. While this can work when a distribution is normal, it is difficult to assess the normality of a dataset with so few samples as it is not advisable to employ the central limit theorem to assume normality in these contexts (Motulsky, 2026a). Other options include non-parametric tests for confidence intervals, the confidence intervals of the median, and using quartiles to determine the range, however it is not entirely clear whether these methods are being used in other studies as they typically state simply that they have determined the confidence interval of the mean. As stated, issues such as skewness and small sample size in the case of this study are not necessarily abnormal, and so it is unclear whether other methods should be used to confirm the best option in these cases where further samples are not available to confirm the nature of normality. Other studies employ the use of the full range of bioavailable studies, which may appear to be a good alternative when using localized faunal remains as clear outliers may be excluded but a broader range can be employed to avoid reducing locality too far, however this too requires significant assumptions to be made regarding the nature of the archaeological site, which would not have been ideal at WF100. Ultimately, the study of Sr isotope ratios in Jordan remains an exciting and complex approach to clarifying the nature of social organization in the EBA Levant with great potential. In order to harness the full potential of this method however, more in depth conversations need to be had regarding the specifics of this type of analysis to ensure the most appropriate approaches are being used in the interest of minimal destruction of remains as well as scientific rigour.

5.4.1 Conclusions

This study has demonstrated that not only are the techniques used to measure mobility in many studies obscuring the complexity of social, environmental, and individual embodiment in human biology, but also that bioarchaeological methods such as LA-MC-ICP-MS paired with theoretically informed methodologies can successfully open windows into new aspects of the lives of individuals in prehistoric contexts. Despite evidence of wall like structures at WF100 (G. Barker et al., 2007; Barker et al., 2000; Dolphin & Adams, 2024), which some may consider to be defensive structures (Wright et al., 1998) this study argues that the social organization and use of the local area at WF100 defies the typical image of EBA urban settlements without indications of a lack of social complexity. The patterns identified in this dataset indicate that while common patterns of socially informed and age defined movement may have existed for some individuals, particularly between 8 and 11 years of age, a large subset of individuals were often not from the local area or travelled intermittently to and from the area, especially in their early childhoods. This suggests that the children at this site were diverse in relation to their lives on the landscape, and further contextual evidence may allow for further elucidation of the intersections between mobility and the social lives of these individuals with particular attention paid to sub-regionally specific pastoralism and role specialization. Furthermore, the indication of more mobility than originally expected emphasizes the importance of aligning these individual regional analysis with other regions to understand not only the local and temporal social organization, but also how these regionally specific sites may have interacted during these time periods as a function of a broader local community who could have exchanged social practices as they encountered each other (Chesson, 2023; Tilley & Cameron-Daum, 2017).

5.4.2 Future directions

Studies of human mobility are essential to answering a variety of questions about prehistory and can be an essential tool for bioarchaeologists as embodiment theory is further integrated into more traditional archaeological research landscapes. This study has highlighted many of the interesting ways in which LA-MC-ICP-MS can be used to study a region which has lost traditional insights as a result of looting, and ultimately, time. Future research that we hope will be conducted in the future include a comprehensive isoscape of the Wadi Faynan region as well as exploring whether further integration of LA-MC-ICP-MS in mobility research is feasible in the modern research environment. With regard to the previous heavy metal research conducted on these samples, there is reason to further investigate the impacts that these novel insights on the wide variety of mobility and locality of the individuals at WF100 may have on their interpretations. Specifically, this comparison may speak to any co-variability which exists between the Sr isotope ratios and the concentrations of heavy metals to speak to the interplay between these two variables.

Consideration should be made in terms of the scientific rigour of this and other methods for sampling and analysing Sr isotopes in a bioarchaeological context. Ultimately, the study of Sr isotope ratios in Jordan remains an exciting and complex approach to clarifying the nature of social organization in the EBA Levant with great research potential. In order to fulfill this potential more in-depth conversations need to be had regarding the specifics of this type of analysis, to ensure the most appropriate approaches are being used in the interest of minimal destruction of remains as well as the preservation of scientific rigour. This study, while not meant to be a critique of past studies, serves as a reminder of the importance of incorporating reflexive

and critical analysis in bioarchaeological studies. The importance of open conversations between researchers to enable better research methodology and transparency enhances the quality of our research. Furthermore, this transparency and open communication allow researchers to better understand individual sites as a unique part of the social ecosystems, rather than in isolation or as a generalization of the whole.

References

Adams, R. (2008). Archaeology in Jordan: A brief history. In R. Adams (Ed.), *Jordan: An archaeological reader*. Equinox Pub.

Agarwal, S. C. (2016). Bone morphologies and histories: Life course approaches in bioarchaeology. *American Journal of Physical Anthropology*, *159*(S61), 130–149. https://doi.org/10.1002/ajpa.22905

Agarwal, S. C., & Beauschesne, P. (2011). It is notcarved in bone: Development and plasticity of the aged skeleton. In S. C. Agarwal & B. A. Glencross, *Social Bioarchaeology* (pp. 312–332).

Agarwal, S. C., & Glencross, B. A. (2011). Building a Social Bioarchaeology. In S. C. Agarwal & B. A. Glencross (Eds.), *Social Bioarchaeology* (1st ed., pp. 1–11). Wiley. https://doi.org/10.1002/9781444390537.ch1

Alpaslan-Roodenberg, S., Anthony, D., Babiker, H., Bánffy, E., Booth, T., Capone, P., Deshpande-Mukherjee, A., Eisenmann, S., Fehren-Schmitz, L., Frachetti, M., Fujita, R., Frieman, C. J., Fu, Q., Gibbon, V., Haak, W., Hajdinjak, M., Hofmann, K. P., Holguin, B., Inomata, T., … Zahir, M. (2021). Ethics of DNA research on human remains: Five globally applicable guidelines. *Nature*, *599*(7883), 41–46. https://doi.org/10.1038/s41586-021-04008-x

Al-Shorman, A., Perry, M., & Coleman, D. (2025). Ancient mobility in northern Jordan during the Roman and Byzantine periods using stable strontium isotope analysis of human dental enamel. *Journal of Archaeological Science: Reports*, *61*, 104879. https://doi.org/10.1016/j.jasrep.2024.104879

Barker, G., Adams, R., Creighton, O., El-Rishi, H., Gilbertson, D. D., Grattan, J. P., Hunt, C., Newson, P., Pyatt, B., & Reynolds, T. (2007). 8. Chalcolithic (c.5000–3600 cal. Bc) and Bronze Age (c.3600–1200 cal. Bc) settlement in Wadi Faynan: Metallurgy and social complexity. In G. Barker, D. D. Gilbertson, & D. J. Mattingly, *Archaeology and desertification: The Wadi Faynan landscape survey, Southern Jordan*. Oxbow Books.

Barker, G. W., Adams, R., Creighton, O. H., Daly, P., Gilbertson, D. D., Grattan, J. P., Hunt, C. O., Mattingly, D. J., McLaren, S. J., Newson, P., Palmer, C., Pyatt, F. B., Reynolds, T. E. G., Smith, H., Tomber, R., & Truscott, A. J. (2000). Archaeology and Desertification in the Wadi Faynan: The Fourth (1999) Season of the Wadi Faynan Landscape Survey. *Levant*, *32*(1), 27–52. https://doi.org/10.1179/lev.2000.32.1.27

Boethius, A., Ahlström, T., Kielman-Schmitt, M., Kjällquist, M., & Larsson, L. (2022). Assessing laser ablation multi-collector inductively coupled plasma mass spectrometry as a tool to study archaeological and modern human mobility through strontium isotope analyses of tooth enamel. *Archaeological and Anthropological Sciences*, *14*(5), 97. https://doi.org/10.1007/s12520-022-01556-9

Booth, T., Roberts, C. A., & Squires, K. (2020). The ethics of sampling human skeletal remains for destructive analysis. In K. Squires, D. Errickson, & N. Márquez-Grant, *Ethical approaches to human remains: A global challenge in Bioarchaeology and forensic anthropology* (pp. 265–297). Springer.

Borofsky, R., & De Lauri, A. (2019). Public Anthropology in Changing Times. *Public Anthropologist*, *1*(1), 3–19. https://doi.org/10.1163/25891715-00101002

Brès, E. F., Reyes-Gasga, J., & Hemmerlé, J. (2021). Human Tooth Enamel, a Sophisticated Material. In M. Goldberg & P. Den Besten (Eds.), *Extracellular Matrix*

Biomineralization of Dental Tissue Structures (pp. 243–259). Springer International Publishing. https://doi.org/10.1007/978-3-030-76283-4_9

Budd, P., Montgomery, J., Barreiro, B., & Thomas, R. G. (2000). Differential diagenesis of strontium in archaeological human dental tissues. *Applied Geochemistry*, *15*(5), 687–694. https://doi.org/10.1016/S0883-2927(99)00069-4

Buikstra, J. E., DeWitte, S. N., Agarwal, S. C., Baker, B. J., Bartelink, E. J., Berger, E., Blevins, K. E., Bolhofner, K., Boutin, A. T., Brickley, M. B., Buzon, M. R., de la Cova, C., Goldstein, L., Gowland, R., Grauer, A. L., Gregoricka, L. A., Halcrow, S. E., Hall, S. A., Hillson, S., … Zakrzewski, S. R. (2022). Twenty-first century bioarchaeology: Taking stock and moving forward. *American Journal of Biological Anthropology*, *178*(S74), 54–114. https://doi.org/10.1002/ajpa.24494

Cavazzuti, C., Skeates, R., Millard, A. R., Nowell, G., Peterkin, J., Brea, M. B., Cardarelli, A., & Salzani, L. (2019). Flows of people in villages and large centres in Bronze Age Italy through strontium and oxygen isotopes. *PLOS ONE*, *14*(1), e0209693. https://doi.org/10.1371/journal.pone.0209693

Chesson, M. S. (2001). Embodied Memories of Place and People: Death and Society in an Early Urban Community. *Archaeological Papers of the American Anthropological Association*, *10*(1), 100–113. https://doi.org/10.1525/ap3a.2001.10.1.100

Chesson, M. S. (2023). Early Bronze Age IA mortuary practices and difference on the south-eastern Dead Sea Plain, Jordan. *Levant*, *55*(1), 61–77. https://doi.org/10.1080/00758914.2022.2151265

Chesson, M. S., & Goodale, N. (2014). Population aggregation, residential storage and socioeconomic inequality at Early Bronze Age Numayra, Jordan. *Journal of Anthropological Archaeology*, *35*, 117–134. https://doi.org/10.1016/j.jaa.2014.02.002

Coffin, J., Dolphin, A. E., Jackes, M., Yakymchuk, C., & Perrin, T. (2022). Exploring childhood mobility in Neolithic Southern France (Roquemissou) using incremental analyses of Sr isotope ratios in tooth enamel. *Journal of Archaeological Science: Reports*, *42*, 103417. https://doi.org/10.1016/j.jasrep.2022.103417

De León, J. (2013). Undocumented migration, use wear, and the materiality of habitual suffering in the Sonoran Desert. *Journal of Material Culture*, *18*(4), 321–345. https://doi.org/10.1177/1359183513496489

Dolphin, A. E., & Adams, R. B. (2024). Something old, something new: Ongoing revelations within the Faynan Landscape. *Palestine Exploration Quarterly*, *156*(2), 179–195. https://doi.org/10.1080/00310328.2023.2171954

Dolphin, A. E., Teeter, M. A., White, C. D., & Longstaffe, F. J. (2016). Limiting the impact of destructive analytical techniques through sequential microspatial sampling of the enamel from single teeth. *Journal of Archaeological Science: Reports*, *5*, 537–541. https://doi.org/10.1016/j.jasrep.2016.01.009

Ellam, R., & Ellam, R. (2016). 1. Identical outsides … different insides. In *Isotopes: A Very Short Introduction* (pp. 1–9). Oxford University Press. https://doi.org/10.1093/actrade/9780198723622.003.0001

El-Rishi, H., Gilbertson, D. D., Hunt, C., Grattan, J. P., McLaren, S. J., Pyatt, B., Duller, G., Gillmore, G., & Phillips, P. (2007). The past and present landscapes of the Wadi Faynan: Geoarchaeological approaches and frameworks. In G. Barker, D. D. Gilbertson, & D. J.

Mattingly, *Archaeology and desertification: The Wadi Faynan landscape survey, Southern Jordan* (pp. 59–95). Oxbow Books.

Flockhart, D. T. T., Kyser, T. K., Chipley, D., Miller, N. G., & Norris, D. R. (2015). Experimental evidence shows no fractionation of strontium isotopes (^{87} Sr/^{86} Sr) among soil, plants, and herbivores: Implications for tracking wildlife and forensic science. *Isotopes in Environmental and Health Studies*, *51*(3), 372–381. https://doi.org/10.1080/10256016.2015.1021345

Gregoricka, L. A. (2021). Moving Forward: A Bioarchaeology of Mobility and Migration. *Journal of Archaeological Research*, *29*(4), 581–635. https://doi.org/10.1007/s10814-020-09155-9

Gregoricka, L. A., Ullinger, J., & Sheridan, S. G. (2020). Status, kinship, and place of burial at Early Bronze Age Bab adh-Dhra': A biogeochemical comparison of charnel house human remains. *American Journal of Physical Anthropology*, *171*(2), 319–335. https://doi.org/10.1002/ajpa.23982

Hillson, S. (2014). *Tooth Development in Human Evolution and Bioarchaeology* (1st ed.). Cambridge University Press. https://doi.org/10.1017/CBO9780511894916

Hillson, S. (2024). *Dental anthropology* (Second edition.). Cambridge University Press.

Hogg, E. A., Welch, J. R., & Ferris, N. (2017). Full Spectrum Archaeology. *Archaeologies*, *13*(1), 175–200. https://doi.org/10.1007/s11759-017-9315-9

Honeychurch, W., & Makarewicz, C. A. (2016). The Archaeology of Pastoral Nomadism. *Annual Review of Anthropology*, *45*(1), 341–359. https://doi.org/10.1146/annurev-anthro-102215-095827

Ingman, T., Eisenmann, S., Skourtanioti, E., Akar, M., Ilgner, J., Ruscone, G. A. G., Roux, P. le, Shafiq, R., Neumann, G. U., Keller, M., Freund, C., Marzo, S., Lucas, M., Krause, J., Roberts, P., Yener, K. A., & Stockhammer, P. W. (2021). Human mobility at Tell Atchana (Alalakh), Hatay, Turkey during the 2nd millennium BC: Integration of isotopic and genomic evidence. *PLOS ONE*, *16*(6), e0241883. https://doi.org/10.1371/journal.pone.0241883

Kaltenbach, H.-M. (2012). *A Concise Guide to Statistics*. Springer. https://doi.org/10.1007/978-3-642-23502-3

Kiddey, R. (2020). I'll Tell You What I Want, What I Really, Really Want! Open Archaeology that Is Collaborative, Participatory, Public, and Feminist. *Norwegian Archaeological Review*, *53*(1), 23–40. https://doi.org/10.1080/00293652.2020.1749877

Kramer, R. T., King, C. L., Buckley, H. R., Jaouen, K., Boyd, D. A., Kiko, L., Trost, M., Petchey, F., & Kinaston, R. L. (2021). Strontium (Sr/Sr) isotope analysis of the Namu skeletal assemblage: A study of past human migration on Taumako, a Polynesian Outlier in the eastern Solomon Islands. *American Journal of Physical Anthropology*, *174*(3), 479–499. https://doi.org/10.1002/ajpa.24179

Kukutai, T., & Black, A. (2024). CARE-ing for Indigenous nonhuman genomic data—Rethinking our approach. *Science*, *385*(6708), eadr2493. https://doi.org/10.1126/science.adr2493

Leatherman, T., & Goodman, A. (2020). Building on the biocultural syntheses: 20 years and still expanding. *American Journal of Human Biology*, *32*(4), e23360. https://doi.org/10.1002/ajhb.23360

Li, W., Zhang, Y., Babajko, S., & Besten, P. D. (2021). Enamel Matrix Biomineralization: The Role of pH Cycling. In M. Goldberg & P. Den Besten (Eds.), *Extracellular Matrix Biomineralization of Dental Tissue Structures* (pp. 271–293). Springer International Publishing. https://doi.org/10.1007/978-3-030-76283-4_11

Lock, M., & Nguyen, V.-K. (2010). *An Anthropology of Biomedicine*.

Manton, D. J., Fernando, J. R., & Reynolds, E. C. (2025). Remineralisation and Biomimetics: Remineralisation Agents and Fluoride Therapy. In E. Eden (Ed.), *Evidence-Based Caries Prevention* (pp. 65–82). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-79152-9_4

Mass Spectrometer. (2021). In *Encyclopedic Dictionary of Archaeology* (pp. 825–825). Springer, Cham. https://doi.org/10.1007/978-3-030-58292-0_130221

Mass Spectrometer, Inductively Coupled Plasma. (2020). In *Compendium of Biomedical Instrumentation* (pp. 1233–1238). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119288190.ch230

Meijer, J. (2018). *Exploring the origins and mobility of the medieval monastic inhabitants of a cave church in Gurat, France using strontium isotope analysis*. University of Waterloo.

Mithen, S., Ahmed Rabbani, M., & Rabbani, M. (2025). Introduction. In S. Mithen, M. A. Rabbani, & M. Rabbani, *Cultural Heritage, Community Engagement and Sustainable Tourism* (1st ed., pp. 1–9). Routledge. https://doi.org/10.4324/9781003491071-1

Mithen, S., Finlayson, B., Al-Nammari, F., Palmer, C., Selim, G., Jacobs, J., Jamieson, E., & Maslamani, N. (2025). The Faynan Heritage Project: Developing a local museum within a rural bedouin community of southern Jordan. In S. Mithen, M. A. Rabbani, & M.

Rabbani, *Cultural Heritage, Community Engagement and Sustainable Tourism* (1st ed., pp. 13–33). Routledge. https://doi.org/10.4324/9781003491071-3

Moon, C., Márquez-Grant, N., Squires, K., & Errickson, D. (2020). What Remains? Human Rights After Death. In K. Squires, D. Errickson, & N. Márquez-Grant, *Ethical Approaches to Human Remains* (pp. 39–58). Springer. https://doi.org/10.1007/978-3-030-32926-6_3

Motulsky, H. J. (2026a). *GraphPad Statistics Guide*. http://www.graphpad.com/guides/prism/10/statistics/index.htm

Motulsky, H. J. (2026b). Principles of Statistics. In H. J. Motulsky, *GraphPad Statistics Guide*. http://www.graphpad.com/guides/prism/10/statistics/index.htm

Nakano, Y., DenBesten, P., & Goldberg, M. (2021). Structure of Collagen-Derived Mineralized Tissues (Dentin, Cementum, and Bone) and Non-collagenous Extra Cellular Matrix of Enamel. In M. Goldberg & P. Den Besten (Eds.), *Extracellular Matrix Biomineralization of Dental Tissue Structures* (pp. 3–34). Springer International Publishing. https://doi.org/10.1007/978-3-030-76283-4_1

Neff, H. (2012). Laser Ablation ICP-MS in Archaeology. In M. S. Lee (Ed.), *Mass Spectrometry Handbook* (1st ed., pp. 829–843). Wiley. https://doi.org/10.1002/9781118180730.ch37

Nicolle, C. (2023). Beyond urbanization, regional settlement pattern in south-eastern Levant during the Early Bronze Age. *Levant*. (world). https://www.tandfonline.com/doi/full/10.1080/00758914.2022.2151225

Ortner, D. J., & Frohlich, B. (2007). The EB IA tombs and burials of Bâb edh-Dhrâ, Jordan: A bioarchaeological perspective on the people. *International Journal of Osteoarchaeology*, *17*(4), 358–368. https://doi.org/10.1002/oa.907

Palmer, C., Gilbertson, D. D., El-Rishi, H., Hunt, C., Grattan, J. P., & Pyatt, B. (2007). The Wadi Faynan today: Landscape, environment, people. In G. Barker, D. D. Gilbertson, & D. J. Mattingly, *Archaeology and desertification: The Wadi Faynan landscape survey, Southern Jordan* (pp. 25–58). Oxbow Books.

Perry, M. A. (Ed.). (2012). *Bioarchaeology and Behavior: The People of the Ancient Near East*. University Press of Florida. https://doi.org/10.5744/florida/9780813042299.001.0001

Perry, M. A., Coleman, D., & Delhopital, N. (2008). Mobility and exile at 2nd century A.D. khirbet edh-dharih: Strontium isotope analysis of human migration in western Jordan. *Geoarchaeology*, *23*(4), 528–549. https://doi.org/10.1002/gea.20230

Perry, M. A., Coleman, D. S., Dettman, D. L., & al-Shiyab, A. H. (2009). An isotopic perspective on the transport of Byzantine mining camp laborers into southwestern Jordan. *American Journal of Physical Anthropology*, *140*(3), 429–441. https://doi.org/10.1002/ajpa.21085

Perry, M. A., Jennings, C., & Coleman, D. S. (2017). Strontium isotope evidence for long-distance immigration into the Byzantine port city of Aila, modern Aqaba, Jordan. *Archaeological and Anthropological Sciences*, *9*(5), 943–964. https://doi.org/10.1007/s12520-016-0314-3

Philip, G. (2008a). The Early Bronze Age I-III. In R. Adams (Ed.), *Jordan: An archaeological reader* (pp. 161–226). Equinox Pub.

Price, T. D., Burton, J. H., & Bentley, R. A. (2002). The Characterization of Biologically Available Strontium Isotope Ratios for the Study of Prehistoric Migration. *Archaeometry*, *44*(1), 117–135. https://doi.org/10.1111/1475-4754.00047

Robbins Schug, G., Halcrow, S. E., & de la Cova, C. (2025). They Are People Too: The Ethics of Curation and Use of Human Skeletal Remains for Teaching and Research. *American Journal of Biological Anthropology*, *186*(2), e70013. https://doi.org/10.1002/ajpa.70013

Rossi, M., Iacumin, P., & Venturelli, G. (2024). 87Sr/86Sr Isotope Ratio as a Tool in Archaeological Investigation: Limits and Risks. *Quaternary*, *7*(1), Article 1. https://doi.org/10.3390/quat7010006

Schrader, S. A., & Torres-Rouff, C. (2020). Embodying bioarchaeology. In C. M. Cheverko, J. R. Prince-Buitenhuys, & M. Hubbe (Eds.), *Theoretical Approaches in Bioarchaeology* (1st ed., pp. 15–27). Routledge. https://doi.org/10.4324/9780429262340-2

Squires, K., Errickson, D., & Márquez-Grant, N. (2020). *Ethical approaches to human remains: A global challenge in bioarchaeology and forensic anthropology*. Springer.

Stahl, A. B. (2020). Assembling "Effective Archaeologies" toward Equitable Futures. *American Anthropologist*, *122*(1), 37–50. https://doi.org/10.1111/aman.13365

Stantis, C., de la Cova, C., Lippert, D., & Sholts, S. B. (2023). Biological anthropology must reassess museum collections for a more ethical future. *Nature Ecology & Evolution*, *7*(6), 786–789. https://doi.org/10.1038/s41559-023-02036-6

Szostek, K., Stepańczak, B., Szczepanek, A., Kępa, M., Głąb, H., Jarosz, P., Włodarczak, P., Tunia, K., Pawlyta, J., Paluszkiewicz, C., & Tylko, G. (2011). Diagenetic signals from ancient human remains—Bioarchaeological applications. *Mineralogia*, *42*(2–3), 93–112. https://doi.org/10.2478/v10002-011-0009-4

Tilley, C., & Cameron-Daum, K. (2017). The anthropology of landscape: Materiality, embodiment, contestation and emotion. In *Anthropology of Landscape: The*

Extraordinary in the Ordinary (pp. 1–22). UCL Press. (4q). https://doi.org/10.2307/j.ctt1mtz542

Vanhaecke, F. (2012). Single-Collector Inductively Coupled Plasma Mass Spectrometry. In F. Vanhaecke & P. Degryse (Eds.), *Isotopic Analysis* (1st ed., pp. 31–75). Wiley. https://doi.org/10.1002/9783527650484.ch2

Voss, B. L. (2018). The Archaeology of Precarious Lives: Chinese Railroad Workers in Nineteenth-Century North America. *Current Anthropology*, *59*(3), 287–313. https://doi.org/10.1086/697945

Wathen-Avila, C., Bengtsson, F., Isaksson, S., Vretemark, M., Eriksson, G., & Lidén, K. (2025). They came from near and far – Strontium isotope analysis of people buried at the early Christian site of Varnhem, southwestern Sweden. *Journal of Archaeological Science: Reports*, *67*, 105387. https://doi.org/10.1016/j.jasrep.2025.105387

Wieser, M., Schwieters, J., & Douthitt, C. (2012). Multi-Collector Inductively Coupled Plasma Mass Spectrometry. In F. Vanhaecke & P. Degryse (Eds.), *Isotopic Analysis* (1st ed., pp. 77–91). Wiley. https://doi.org/10.1002/9783527650484.ch3

Wright, K., Najjar, M., Last, J., Moloney, N., Flender, M., Gower, J., Jackson, N., Kennedy, A., & Shafiq, R. (1998). The Wadi Faynan Fourth and Third Millennia Project, 1997: Report on the First Season of Test Excavations at Wadi Faynan 100. *Levant*, *30*(1), 33–60. https://doi.org/10.1179/007589198790217142

Wu, N., Zhang, J., Mao, H., Zhang, G., & Zhao, Z. (2024). Geochemical behavior of stable strontium isotopes during continental weathering process: A review. *Geosystems and Geoenvironment*, *3*(2), 100144. https://doi.org/10.1016/j.geogeo.2022.100144

Zuckerman, M. K., & Armelagos, G. J. (2011). The origins of biocultural dimensions in bioarchaeology. In S. C. Agarwal & B. A. Glencross, *Social Bioarchaeology* (pp. 13–43).

Zuckerman, M. K., Kamnikar, K. R., & Mathena, S. A. (2014a). Recovering the 'Body Politic': A Relational Ethics of Meaning for Bioarchaeology. *Cambridge Archaeological Journal*, *24*(3), 513–522. https://doi.org/10.1017/S0959774314000766

Zuckerman, M. K., Kamnikar, K. R., & Mathena, S. A. (2014b). *Recovering the 'Body Politic': A Relational Ethics of Meaning for Bioarchaeology | Cambridge Archaeological Journal | Cambridge Core*. https://www-cambridge-org.proxy.lib.uwaterloo.ca/core/journals/cambridge-archaeological-journal/article/recovering-the-body-politic-a-relational-ethics-of-meaning-for-bioarchaeology/10660DA5F1349303B820D58384F3EBBA

Appendices

Appendix A: Methodological principles of isotopic analysis

A.1 Mass spectrometry

Fundamental principles of mass spectrometry hinge on the ability of instrumentation to separate and detect differences in mass to charge ratio for different ions, which then can be translated to quantitative data ("Mass Spectrometer," 2021; "Mass Spectrometer, Inductively Coupled Plasma," 2020; Vanhaecke, 2012; Wieser et al., 2012). As such, differences in mass spectrometers may arise because of the exact technology used, but they will all employ similar mechanisms for ion production, separation, and measurement.

A.2 Ca^{2+} substitution with Sr^{2+} basic principles and equilibrium

Mineralization of the enamel matrix occurs as a result of the degradation of the organic matrix and subsequent facilitation of hydroxyapatite formation by enamel matrix proteins (ameloblasts and associated proteins) (Brès et al., 2021; Li et al., 2021). Similar ions (those with similar characteristics and ion charges) may also compete with these proteins and fit into the hydroxyapetite structures as the Ca^{2+} is transported from the blood to the enamel matrix. The mechanisms which allow for the substitution of other ions such as Sr^{2+} into the structure of hydroxyapatite without significantly affecting the crystallite structures are highly complex and diverse, however they are made possible by its similar characteristics to Ca^{2+} because equilibrium is maintained in the hydroxyapatite molecule itself (Brès et al., 2021; Hillson, 2014).

Appendix B: Supplementary materials

B.1 Descriptive statistics

Descriptive statistics of all human data sorted by sample. Evaluated for minimum, maximum, range, mean, standard deviation, standard error of mean, and 95% confidence intervals of the mean for each sample. All produced values are tests of the cleaned raw data which excludes cracks and instrumental interference.

Descriptive statistics		A	B	C	D	E	F	G
		01	002	02	03	04	06	08
1	Number of values	444	400	637	374	356	362	421
2								
3	Minimum	0.7033	0.7074	0.7048	0.7044	0.7062	0.7081	0.7057
4	Maximum	0.7087	0.7095	0.7097	0.7086	0.7089	0.7104	0.7100
5	Range	0.005455	0.002193	0.004832	0.004280	0.002687	0.002339	0.004293
6								
7	Mean	0.7056	0.7087	0.7075	0.7064	0.7076	0.7092	0.7076
8	Std. Deviation	0.0009252	0.0003355	0.0009302	0.0008339	0.0004443	0.0004340	0.0008137
9	Std. Error of Mean	4.391e-005	1.678e-005	3.686e-005	4.312e-005	2.355e-005	2.281e-005	3.966e-005
10								
11	Lower 95% CI of mean	0.7055	0.7087	0.7074	0.7064	0.7076	0.7092	0.7076
12	Upper 95% CI of mean	0.7057	0.7087	0.7075	0.7065	0.7077	0.7093	0.7077

	H	I	J	K	L	M	N	O	P
	09	11	12	13	14	014	15	17	19
1	415	379	395	228	392	129	391	459	318
2									
3	0.7084	0.7058	0.7086	0.7061	0.7052	0.7080	0.7081	0.7076	0.7082
4	0.7110	0.7104	0.7102	0.7096	0.7091	0.7102	0.7103	0.7104	0.7098
5	0.002534	0.004585	0.001661	0.003424	0.003879	0.002243	0.002191	0.002814	0.001603
6									
7	0.7096	0.7075	0.7093	0.7077	0.7073	0.7089	0.7092	0.7090	0.7090
8	0.0004940	0.0007369	0.0002958	0.0006440	0.0007615	0.0004615	0.0003806	0.0004397	0.0002920
9	2.425e-005	3.785e-005	1.488e-005	4.265e-005	3.846e-005	4.063e-005	1.925e-005	2.052e-005	1.638e-005
10									
11	0.7095	0.7074	0.7093	0.7076	0.7072	0.7088	0.7091	0.7089	0.7090
12	0.7096	0.7075	0.7093	0.7078	0.7074	0.7090	0.7092	0.7090	0.7090

	Z	AA	AB	AC	AD	AE	AF	AG
	031	032	033	091*	113	116*	121	167
1	301	385	165	475	750	381	234	342
2								
3	0.7081	0.7078	0.7077	0.7075	0.7077	0.7032	0.7083	0.7078
4	0.7100	0.7099	0.7103	0.7094	0.7123	0.7297	0.7109	0.7097
5	0.001913	0.002138	0.002600	0.001910	0.004582	0.02649	0.002612	0.001889
6								
7	0.7088	0.7089	0.7089	0.7083	0.7095	0.7091	0.7096	0.7088
8	0.0002598	0.0003457	0.0004160	0.0002893	0.0007654	0.001428	0.0004777	0.0003700
9	1.498e-005	1.762e-005	3.239e-005	1.328e-005	2.795e-005	7.316e-005	3.123e-005	2.001e-005
10								
11	0.7088	0.7088	0.7088	0.7083	0.7095	0.7089	0.7095	0.7087
12	0.7088	0.7089	0.7090	0.7084	0.7096	0.7092	0.7096	0.7088

	Q	R	S	T	U	V	W	X	Y
	21	22	23	24	25	26	28	028*	29
1	320	365	274	624	509	381	324	214	418
2									
3	0.7084	0.7077	0.7082	0.7077	0.7081	0.7083	0.7082	0.7079	0.7078
4	0.7102	0.7096	0.7098	0.7096	0.7110	0.7102	0.7104	0.7096	0.7108
5	0.001832	0.001979	0.001609	0.001904	0.002871	0.001961	0.002152	0.001755	0.003010
6									
7	0.7092	0.7086	0.7090	0.7087	0.7093	0.7093	0.7094	0.7087	0.7091
8	0.0003429	0.0003054	0.0002713	0.0003270	0.0004489	0.0002870	0.0003813	0.0003488	0.0004921
9	1.917e-005	1.599e-005	1.639e-005	1.309e-005	1.990e-005	1.470e-005	2.119e-005	2.384e-005	2.407e-005
10									
11	0.7091	0.7086	0.7090	0.7087	0.7093	0.7093	0.7093	0.7086	0.7091
12	0.7092	0.7087	0.7090	0.7087	0.7093	0.7094	0.7094	0.7087	0.7092

	Z	AA	AB	AC	AD	AE	AF	AG
	031	032	033	091*	113	116*	121	167
1	301	385	165	475	750	381	234	342
2								
3	0.7081	0.7078	0.7077	0.7075	0.7077	0.7032	0.7083	0.7078
4	0.7100	0.7099	0.7103	0.7094	0.7123	0.7297	0.7109	0.7097
5	0.001913	0.002138	0.002600	0.001910	0.004582	0.02649	0.002612	0.001889
6								
7	0.7088	0.7089	0.7089	0.7083	0.7095	0.7091	0.7096	0.7088
8	0.0002598	0.0003457	0.0004160	0.0002893	0.0007654	0.001428	0.0004777	0.0003700
9	1.498e-005	1.762e-005	3.239e-005	1.328e-005	2.795e-005	7.316e-005	3.123e-005	2.001e-005
10								
11	0.7088	0.7088	0.7088	0.7083	0.7095	0.7089	0.7095	0.7087
12	0.7088	0.7089	0.7090	0.7084	0.7096	0.7092	0.7096	0.7088

B.2 Bioavailable strontium normality tests and descriptive statistics

Number of values	**11**
Minimum	0.7080
25% Percentile	0.7084
Median	0.7088
75% Percentile	0.7093
Maximum	0.7101
Range	0.002038
95% CI of median	
Actual confidence level	98.83%
Lower confidence limit	0.7082
Upper confidence limit	0.7094
Mean	0.7088
Std. Deviation	0.0005959
Std. Error of Mean	0.0001797

Lower 95% CI of mean	0.7084
Upper 95% CI of mean	0.7092
Coefficient of variation	0.08406%
Skewness	0.7973
Kurtosis	0.4814

Compare normal and lognormal	
Probability normal (Gaussian)	49.92%
Probability lognormal	50.08%
Likelihood ratio (LR)	0.9970
1/LR	1.003
Which distribution is more likely?	Lognormal
Test for normal distribution	
D'Agostino & Pearson test	
K2	1.857
P value	0.3952
Passed normality test (alpha=0.05)?	Yes
P value summary	ns
Anderson-Darling test	
A2*	0.2410
P value	0.7048
Passed normality test (alpha=0.05)?	Yes
P value summary	ns
Shapiro-Wilk test	
W	0.9506
P value	0.6520

Passed normality test (alpha=0.05)?	Yes
P value summary	ns
Kolmogorov-Smirnov test	
KS distance	0.1221
P value	>0.1000
Passed normality test (alpha=0.05)?	Yes
P value summary	ns
Test for lognormal distribution	
D'Agostino & Pearson test	
K2	1.846
P value	0.3973
Passed lognormality test (alpha=0.05)?	Yes
P value summary	ns
Anderson-Darling test	
A2*	0.2405
P value	0.7067
Passed lognormality test (alpha=0.05)?	Yes
P value summary	ns
Shapiro-Wilk test	
W	0.9508
P value	0.6540
Passed lognormality test (alpha=0.05)?	Yes
P value summary	ns
Kolmogorov-Smirnov test	
KS distance	0.1220
P value	>0.1000
Passed lognormality test (alpha=0.05)?	Yes

P value summary	ns
Number of values	11
Impossible values in lognormal distributions	
Number of zeroes	0
Number of negative values	0