Exploring the Origins and Mobility of the Medieval Monastic Inhabitants of a Cave Church in Gurat, France using Strontium Isotope Analysis

by

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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.

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Abstract

Researchers inevitably must destroy a portion of their sample to conduct stable isotope analyses and obtain the chemical signatures embedded within biological hard tissues such as tooth or bone. However, the degree to which a sample is destroyed depends upon the chosen analytical technique. In order to conduct strontium (Sr) isotope analysis on dental and skeletal tissues acquired from Gurat, France the research presented here employs laser ablation multi-collector inductively coupled plasma-mass spectrometry (LA-MC-ICP-MS). The comparison of $^{87}Sr/^{86}Sr$ values allows researchers to explore past individual and/or population mobility.

Within Gurat, a small village located in the region of Poitou-Charentes in southwestern France, is a hand-carved limestone cave church that is one of several mid-sized structures that likely developed from a hermitic site to a centre for monasticism by the High Middle Ages. Gurat is unique in that abundant archaeological data and a collection of unstudied human remains are available for analysis after remaining in storage for fifty years. This research therefore represents the first effort to understand who the people at Gurat were and what the meaning of the site may have been locally and regionally. Overall, the study showed that many of the Gurat individuals were in fact migrants to the village. In turn, this reflects and reinforces the regional importance of this medieval monastic centre. This research also highlights the ability of laser ablation to minimize destruction of irreplaceable bioarchaeological material.

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List of Abbreviations

AAA	American Anthropological Association
AAPA	American Association of Physical Anthropologists
AD	After Death
Ca	Calcium
CI	Crystallinity Index
FTIR	Fourier Transform Infrared Spectrometry
Gu	Gurat
LA-MC-ICP-MS	Laser Ablation Multi-Collector Inductively Coupled Plasma Mass Spectrometry
N	Number
SD	Standard Deviation
SE	Standard Error
Sr	Strontium
^{84}Sr, ^{86}Sr, ^{88}Sr	Stable Strontium Isotopes
^{87}Sr	Radiogenic Strontium Isotope
Rb	Rubidium
^{87}Rb	Radioactive Rubidium Isotope
µm	Micrometres/Microns

Chapter One

Minimizing the Destructive Nature of Bioarchaeological Inquiries

1.1 Introduction

The primary aim of this thesis was to conduct strontium isotope analysis in order to explore the mobility of the medieval monastic inhabitants of a rock-cut cave church in Gurat, France. Due to limited skeletal material coupled with the goal of limiting the destruction of irreplaceable bioarchaeological material, this study employed minimally destructive analytical techniques in order to preserve samples for future study.

Researchers must destroy a portion of their sample to obtain the chemical signatures embedded within biological hard tissues such as tooth or bone. However, the degree to which a sample is destroyed depends upon the chosen analytical technique. As stated by Dolphin et al. (2016), there is a fundamental concern in bioarchaeology with how to best achieve a balance between the preservation of human remains and maximizing data collection via the use of destructive analytical techniques. The public issue component of this thesis therefore discusses the ways in which limiting the destruction of invaluable bioarchaeological material can be achieved in order to address the concerns of both stakeholders and researchers. Additionally, tourism associated with new archaeological inquiries should also be considered as excavations may provide new jobs to local archaeologists and increase local business revenue.

1.2 Availability of Bioarchaeological Materials at Gurat

Excavations took place at the rock-cut cave church in Gurat during the 1960s and 1970s, however, this thesis serves as a foundation for future studies as further research has yet to be undertaken. This current research represents initial efforts to better understand who the Gurat

individuals were and what the local and regional significance of the site might have been. Drawing on archaeological lines of evidence for the study is challenging given that few grave goods were associated with these individuals and research concerning cave dwelling in the Middle Ages is minimal. Therefore, the skeletal remains of the eighteen Gurat individuals may be the only resource available to researchers in order to gain insights with regard to the history of this cave church. It is therefore of the utmost importance to preserve the skeletal material belonging to the Gurat skeletal collection.

1.3 Defining the Public in Public Bioarchaeology

Despite working with the deceased, bioarchaeology engages with several publics, including descendent communities, geographically related communities, and invested parties such as individuals or businesses (Stojanowski and Duncan 2015). For the purposes of this thesis, the term "public" refers to descendent or interested communities, also known as stakeholders, or those who hold interest or concern in a particular endeavour or situation (Adams 2005). Stakeholdership may be extended toward the Christian community, as it is believed that the Gurat individuals were indeed involved with, and part of, a Christian religious order. Additionally, local archaeologists may also be considered stakeholders. This research on minimizing the destructive effects of bioarchaeological studies can be applicable to a multitude of other research projects that involve the handling of biological hard tissues. Thus, the notion of the "public" can be extended to any stakeholder community within the realm of bioarchaeological inquiry.

1.3.a Ethical Considerations

When making use of various isotopic methods, researchers must take into consideration the destructive nature of their work and the ramifications such destruction may have on public communities. In doing so, researchers must ask themselves: do the ends justify the means?

According to the American Association of Physical Anthropologists (AAPA) Code of Ethics (2003) researchers have ethical obligations to: 1) the people and animals that they study; 2) the scholarship and science with which they engage; and 3) the public. The American Anthropological Association (AAA) Code of Ethics (2012) mandates that the conservation, protection, and stewardship of the bioarchaeological record is of principal ethical concern given the irreplaceable nature of materials excavated. "Do no harm" is stated by both ethical codes as the primary principal by which researchers must abide. This philosophy is especially applicable for studies that involve the use of human biological tissues. In using bulk sampling and laser ablation techniques, researchers must destroy a portion of tooth and bone samples and must therefore work within both the ethical guidelines provided by anthropological societies (i.e. AAPA and AAA), as well as the values and belief systems of the appropriate stakeholders.

Within bioarchaeology, researchers must conduct their work while considering the beliefs and best interests of those under study (Rose et al. 2015). Klesert and Powell (1993) assert that researchers do not have the inherent right to access and study human remains and that academic pursuits must be properly contextualized in order to include public interests (348). Hodder (2002) advocates for collaboration and compromise between different interest groups, including archaeologists (academic) and local communities (public). Collaboration has the potential to enrich information that can be obtained through study.

1.3.b Future Public Engagement in Gurat

It is difficult to reach out to stakeholders in Gurat because no excavations are currently taking place. Interested parties have yet to claim ownership or stakeholdership of the Gurat skeletal collection. It is interesting in that, through social media (i.e. Instagram, Facebook), the present Gurat community appear to use the cave Church and the Romanesque church, St. George that sits above the cliff with which the cave church is situated, as sites to attract tourists. Future archaeological excavations should incorporate the narratives of local communities in order to enrich the dataset from anthropological inquiries in Gurat. Building public engagement is currently a work in progress that began in late 2016 with Dr. Michael Gervers, the primary excavator of the site, contacting local archaeologists with regard to future excavations. The social impact (e.g. archaeological tourism) of future anthropological work at Gurat should be taken into consideration (Adams 2005).

1.4 Analytical Techniques and Strontium Isotope Analysis

The analytical technique chosen for a research project can impact the level of sample destruction, as well as the research question(s) that a researcher can explore. Both bulk sampling techniques and laser ablation have been employed in order to use strontium isotope analysis to explore the movement of past individuals and populations. The research in Chapter 2 employs laser ablation, rather than traditional bulk sampling, in order to conduct strontium isotope analysis for the purposes of exploring human mobility. Laser ablation was chosen as the analytical technique for two reasons: 1) in order to minimize the destructive impact on the Gurat skeletal collection and, 2) in order to explore early childhood mobility by micro-sampling strontium isotope values from both early and later forming enamel. The comparison of early and later forming enamel allows for the exploration of mobility during childhood and may even

illuminate maternal mobility in enamel formed *in utero*. Bulk sampling and laser ablation will be compared and contrasted here in order to justify the use of laser ablation employed in Chapter 2.

1.4.a Bulk Sampling

Bulk sampling has been a standard technique used in isotopic studies since the 1980s (Slovak and Paytan 2011). Sometimes referred to as 'solution analysis', bulk sampling is a completely destructive analytical technique in that it involves cutting pieces of bone, or pulling teeth, and reducing them to a fine powder using a mortar and pestle. Between 50 milligrams (mg) to 1 gram (g) of powder are generally required for analysis (Slovak and Paytan 2011, 751). The powder is then fully digested in an acid solution. In relation to isotope studies, this technique has been used for both faunal (Bentley et al. 2003; Copeland et al. 2008) and human teeth (Grupe et al. 1997; Evans et al. 2006), as well as both faunal (Bentley et al. 2003) and human bone (Hewitt 2013). Analytical methods such as Thermal Ionization Mass Spectrometry (TIMS) and Mass Spectrometry (MS) are commonly used to measure the isotopic content of materials dissolved in acid (Kang et al. 2004, 1609).

1.4.a.i Benefits of Bulk Sampling Techniques

Bulk sampling techniques provide both practical and methodological benefits. This method, as illustrated above, may not require the use of specialized laboratory equipment in sample preparation prior to digestion.

The primary benefit of bulk sampling techniques is that, being the traditional approach, they are widely recognized in bioarchaeology as a valid method for analysing stable isotopes. Many studies have set out to explore and address the differing results that are produced by bulk sampling and micro-sampling methods such as laser ablation (i.e. Habicht-Mauche et al. 2002; Copeland et al. 2008; Hewitt 2013). For example, with regard to strontium isotope studies, most

researchers conclude that bulk sampling is a marginally more accurate means to attain the $^{87}Sr/^{86}Sr$ signature in archaeological tooth and bone samples. However, this depends on a variety of factors including the research question and the standards that are used for instrument calibration.

1.4.a.ii Limitations of Bulk Sampling Techniques

Two main problems with utilizing bulk sampling include homogenization of data and total destruction of sample material. A fundamental problem faced by researchers who use bulk sampling techniques is the homogenization of data. Specifically, in reference to dental tissue samples, the time-based elemental and isotopic distribution profiles in teeth are destroyed during bulk analyses (Kang et al. 2004). Total digestion of the sample material "homogenizes the fluctuations in trace element absorption so that the time-specific data locked within each layer of tissue is obscured" (Dolphin 2006, 113). Using this method may limit the inquiries that researchers can explore.

Additionally, bulk sampling limits the amount of material that can be used for future analyses. Slovak and Paytan (2011) state that collecting samples for analysis involves the permanent removal of enamel, dentine and/or bone from an archaeological specimen, and therefore, sample selection must be conducted with caution (751). Preservation concerns not only affect the researcher, but also affect descendent communities and multiple stakeholder groups. Although the usage of bulk sampling techniques can have practical and methodological benefits, their destruction of irreplaceable bioarchaeological material must be considered.

1.4.b Laser Ablation

Laser ablation is a micro-sampling technique that can be applied to hard tissue samples, while minimizing the destruction of irreplaceable bioarchaeological materials. Unlike the

complete dissolution of samples through traditional bulk analyses, laser ablation directs a high-energy pulsed laser beam onto a preselected surface of a sample material (Kang et al. 2004, 1609), leaving sample spots or lines that are not visible to the naked eye. Analytical methods such as multi-collector inductively coupled plasma-mass spectrometry (MC-ICP-MS) can be used to measure the isotopic composition of materials that undergo laser ablation.

In order to prepare a sample for laser ablation, that sample is most often embedded in resin, sectioned and mounted on a slide. In order to section a bone or tooth sample for laser ablation it will most likely be cut so as to expose its interior.

1.4.b.i Benefits of Laser Ablation

Thus, unlike bulk sampling techniques, laser ablation is a minimally destructive microspatial technique, with almost the entire sample remaining available for future research once an analysis is completed. In ablating tooth samples for analysis, for example, laser ablation has the ability to capture retrospective snapshots of the fluctuations of trace element absorption over time. The laser is able to ablate a preselected surface of a sample that can approach the size of approximately five micrometres (μm) (Farell et al. 2012), although researchers most often choose a spot size of 20 μm or more. In teeth, the chosen sample surface can correspond to a particular growth band present in the enamel, dentine or cementum. This correspondence between chemical and microstructural data allows researchers to ask new questions and explore a new type of dataset, one that reflects the retrospective indictors of diet, growth, and development (Dolphin et al. 2005). A researcher must therefore take the research landscape, and instruments available, into consideration when formulating a research question (Boellstorff et al. 2012).

Furthermore, although the sample must be embedded in resin and sectioned to reveal areas of interest, it is also preserved in its section for future analyses. This has immense research

benefits, as samples can be preserved for re-analysis and used to explore new research questions. This is especially useful in the preservation of skeletal remains for future studies when new techniques become available (Rose et al. 1996, 85).

1.4.b.ii Limitations of Laser Ablation

Scholars have reviewed the accuracy of the results yielded from studies employing laser ablation and drawn comparisons with that of bulk sampling analysis (Habicht-Mauche et al. 2002; Copeland et al. 2008; Hewitt 2013). Although in their study using strontium isotope analysis, Copeland et al. (2008) found a slight difference in values yielded from bulk sampling and laser ablation techniques this difference was not significant, and therefore, within acceptable error ranges.

Although minimally destructive, laser ablation may not prove to be an alterative to fully destructive analyses through the lens of the public as the level of destruction may be irrelevant. This may pose as an obstacle when academic researchers and the public must work together. When embarking on isotopic studies, although the research benefits may outweigh the costs of destruction, the interest of public communities must always be taken into consideration and respected.

1.5 Social Aspect of Bioarchaeological Inquiries

According to Purcell (2000), public anthropology works toward directly and indirectly contributing to the public good. In this sense, public bioarchaeology engages with the public in two ways: through physical engagement with descendent communities and/or stakeholders, and through the dissemination of research results and information to an audience outside the academy (Stojanowski and Duncan 2015).

In engaging with stakeholders, future excavations at the rock-cut cave church in Gurat will provide local archaeologists with new jobs. Through the dissemination of research, future excavations may increase tourism, and in turn, provide a new source of revenue for local businesses. The work in Chapter 2 has illustrated that Gurat held regional importance and thus, enriches the knowledge of the local history behind both the cave church and the village itself.

1.6 Concluding Remarks

The research conducted in Chapter 2 was employed whilst ensuring that the least amount of skeletal material was destroyed. Minimizing the destruction of skeletal material overall has both research and social benefits: it has been shown that minimally destructive techniques, such as laser ablation, have immense research benefits that outweigh the use of destructive techniques, such as bulk sampling; it has also been illustrated that incorporating public narratives and the involvement of local stakeholders can provide public benefit in the form of new sources of revenue for local individuals and businesses. The narratives of the Gurat community should thus be taken into consideration if future archaeological excavations take place.

Researchers must ensure that their methodologies are both appropriately justified and well-suited in order to meet the research needs and answer the research question, as well as to satisfy the needs of multiple stakeholder groups.

1.7 Intention for Publication

I intend to publish Chapter 2 of this Master's thesis research in the *International Journal of Osteoarchaeology*. This journal provides an avenue for the publication of original research dealing with human and animal bones from archaeological contexts. Population level studies using biomolecular analyses, including isotopic analyses, are areas of work that are encouraged for submission (International Journal of Osteoarchaeology 2017). The purpose of this research is

to explore the mobility of the medieval monastic inhabitants of the cave church in Gurat and as such, this work aligns with the aims of the *International Journal of Osteoarchaeology*. Through publication in the *International Journal of Osteoarchaeology* this work will contribute to research on medieval monastic life (specifically, in southwestern France) and serve to pave the way for continued excavations in Gurat, France, and for further osteological, histological and chemical investigations of the lives of the people buried there.

Chapter Two

Exploring the Origins and Mobility of the Medieval Monastic Inhabitants of a Cave Church in Gurat, France using Strontium Isotope Analysis

2.1 Introduction

During life, the chemical signature of bodily tissues is determined in part by the food and water ingested, which in turn varies in relation to the local environment. In essence, we are what we eat (and where we drink), with stable isotopes such as strontium (Sr) being deposited in teeth and bones in measurable amounts (Price 2015). The ratio of $^{87}Sr/^{86}Sr$ in tooth enamel reflects the underlying geology where one was born when that enamel formed. Alternatively, when analyzed in bone, the same ratio reflects the location of that person during the last decade of their life, when their bones were remodelling. Comparing $^{87}Sr/^{86}Sr$ in both tooth and bone allows the researcher to contrast mobility during an individual's lifetime: identifying childhood and adulthood mobility. The measurement of $^{87}Sr/^{86}Sr$ in bioarchaeological studies therefore allows for a direct examination of mobility and migration in human, animal, and marine populations. The research presented here details the application of strontium isotope analysis to the study of human skeletal remains buried in Gurat, France. Strontium isotope ratios were used to explore the origins and mobility of the Gurat individuals, and develop a greater understanding of the local and regional significance of the rock-cut cave church in which they were laid to rest.

The rock-cut cave church in Gurat is one of several mid-sized structures that likely developed from a hermitic site to a centre for monasticism by the mid sixteenth century in southwestern France (Gervers 1967). Gurat is, however, unique in that abundant archaeological data and a collection of unstudied human remains are available for analysis after remaining in storage for fifty years. This study represents the first effort to understand who these individuals were and where they might have travelled from by analysing their skeletal remains. In order to

do so, this study utilizes recent advances in micro-spatial isotopic analyses to explore the movement of the Gurat individuals through the geological landscape, contrasting their place(s) of birth with their final resting place.

2.2 Historical and Archaeological Context

Gurat is a small village located in the region of Poitou-Charentes, France. St. George, a Romanesque church built during the late eleventh century, stands atop the cliff in which the rock-cut cave church is situated. Excavations took place there during the late 1960s and early 1970s under the leadership of Dr. Michael Gervers, currently a faculty member in the Department of Historical and Cultural Studies at the University of Toronto.

The cave church of Gurat is one of many rock-cut structures in southwestern France, an area in which cave use has a long history perhaps due to the predominance of calcareous rock within the region (Gervers 1967). Ten other known rock-carved churches exist within a one hundred-kilometre radius of Gurat, out of which only Aubeterre in Charente and Saint Emilion in Gironde are larger than the site in Gurat (Clements and Gruspier n.d.). All of these sites served as Christian ecclesiastical centres, as well as places with which to bury the dead (Gervers 1974).

Coupled with its complex of adjoining grottos, this cave church is situated within a cliff that overlooks the Lixonne River valley. Two pilgrimage routes traversed the village during the Medieval Era: one between Charroux and La Réole (Gervers 1967) and another between Vézelay to Bordeaux through to Northwestern Spain (Stopford 1994). It is likely that the cave church may have originated as early as the fourth century AD (Clements and Gruspier n.d.). Group hermitism was widespread throughout Europe and flourished under Charlemagne in the eighth century, however many hermitages were destroyed during Viking invasions. It is likely that the Gurat cave church was re-established as a site for hermitism before the end of the eleventh century

when the Romanesque village church was constructed (Gervers and Gervers 1974) and later grew into a centre for monasticism (Gervers 1967).

Archaeological lines of evidence, such as analyses of coinage, have helped establish a timeline for life at the cave church. Nine coins excavated from within the cave church have been separated into two categories, the first belonging to the late thirteenth/early fourteenth centuries, and the second belonging to the sixteenth and seventeenth centuries. The earliest date associated with the cave church, as established by the coins, is 1237 – 1286 (Franklin and Gervers 1978). The last date to be associated with activity at the cave church lies roughly between 1655 and 1701 (Franklin and Gervers 1978). The group of coins belonging to the former group were found deposited together in a rock-cut pit, whereas the coins belonging to the latter group were found on the rock floor itself (Franklin and Gervers 1978). Additionally, based upon radiocarbon dating of charcoal fragments found within Grave Hb and analyses of pottery, researchers estimate that this site was occupied around the time of ca.1390 AD (see Franklin and Gervers 1978). However, this absolute date must be noted with caution, as it is unknown at this time if these individuals did indeed represent one population at one point in time, or rather were part of separate groups of population who occupied this site over the span of a few centuries. Due to differences in grave orientation and burial position it is possible that these individuals were in fact buried at different points in time (see Section 2.2.a below). Furthermore, the lack of archaeological evidence after the sixteenth century suggests that the cave church was no longer a site for occupation, but rather a refuge for travellers during the Wars of Religion and later, served as a local dump (Franklin and Gervers 1978).

2.2.a Skeletal Collection

The Gurat Skeletal collection consists of a minimum of eighteen individuals, of which only fourteen were sampled[1] for this research project. Table 2.1 summarizes the age and sex estimations of each individual sampled for this research project (for more information on individual internment and pathology see Appendix A). It is important to note that not all of the burials located at Gurat have been excavated. All individuals currently excavated were buried on a ledge exterior to and east of the cave church entrance (Clements and Gruspier n.d.). The individuals were buried in graves cut from limestone rock: all oriented toward the east.

Grave	Individual	Age in Years	Sex
Ha	Gu 1	50+ Years	Probable Female
Hb	Gu 2	35-50 Years	Probable Male
Hb	Gu 3	20-35 Years	Possible Male?
Hb	Gu 4(5)	4 Years ±12 months	Indeterminate
Hb	Gu MISC	6 Years ± 24 months	Indeterminate
Ja	Gu 6	Adolescent (~14-16 Years)	Probable Female
Ja	Gu 6A	Birth – 3 Years	Indeterminate
Ja	Faunal Ja	N/A	N/A
Dc	Gu 7	35-50 Years	Possible Male
Dc	Gu 8	35-50 Years	Probable Male
Dc	Gu 9	35-50 Years	Possible Male?
Dc	Infant Dc	4 Months ± 2 months	Indeterminate
Dc	Faunal Dc	N/A	N/A
Dd	Gu 10	3 Years ±12 months	Indeterminate
Db	Gu 11	35-50 Years	Indeterminate
Db	Gu 12	20-35 Years	Indeterminate
	Totals:	**Subadult** N = 6 **Young Adults** N = 2 **Middle Adults** N = 5 **Old Adults** N = 1	**Female** N = 2 **Male** N = 5 **Indeterminate Adults** N = 2 **Indeterminate Subadults** N = 5

Table 2.1: Gurat skeletal collection: Age and sex of individuals sampled based upon standards outlined by Buikstra and Ubelaker (1994).

Three sections that were excavated contained graves (sections H, J and D). Burials contained in sections H and J seemed to be undisturbed, whereas burials excavated in section D were disturbed (Clements and Gruspier n.d.). Individuals buried in graves Ha (Gu 1, Gu 1A who

[1] Only tooth and bone samples that were confidently associated with the same individual were sampled for this study.

was not sampled for this research project) and Hb (Gu 2, Gu 3, Gu 4(5), Gu MISC, an additional adult not sampled for this research project) were buried individually in primary burials and were in good condition. The two individuals in grave Ja (Gu 6, Gu 6A) were buried together; it is believed that Gu 6 may have been wrapped upon burial due to the position of the feet (Gervers 1968). Five individuals contained in grave Dc (Gu 7, Gu 8, Gu 9, Infant Dc, an additional adult not sampled for this research project) were buried together, with Gu 8 overlain Gu 9. Grave Dd contains one individual (Gu 10) and is believed to be a secondary burial (Clements and Gruspier n.d.). Grave Db was also believed to be a secondary burial and contains two individuals (Gu 11, Gu 12).

2.3 Mobility Studies: Theory and Method

Researchers have used strontium isotope ratios as indicators of human mobility in archaeology since 1985 (e.g. Ericson 1985; Price et al. 2002, 2004; Bentley et al. 2003, 2004; Montgomery et al. 2010). Ericson (1985) was the first to show that $^{87}Sr/^{86}Sr$ ratios in human bones and teeth could be used as tracers to reveal human residential mobility. In his pilot study, Ericson (1985) explored intermarriage residence patterns of past people whose remains were excavated in California. Through strontium isotope analysis of the second molar, he was able to track the origins of these individuals (Ericson 1985). Strontium isotopes have since been used to explore the mobility of past populations in numerous parts of the world including, but not limited to Western Europe (Evans et al. 2006), Central Europe (Grupe et al. 1997; Bentley et al. 2003, 2004), Eastern Europe (Borić and Price 2013), North America (Ericson 1985; Price et al. 2000; Beard and Johnson 2000), South America (Conlee et al. 2009; Hewitt 2013), North Africa (Tafuri et al. 2006; Buzon et al. 2007) and South Africa (Copeland et al. 2010).

2.3.a Strontium

Strontium (Sr) is an alkaline earth metal with a valence of 2+, has an atomic number of 38, and atomic weight of 87.62. Strontium is found in rock, groundwater, and soil, as well as in plants and animals whose strontium uptake through the food chain reflects the geology of the region in which they are located. Because its ionic radius (1.18 Å) is only slightly larger than that of calcium (Ca) (1.00 Å), Sr^{2+} can substitute for Ca^{2+} in minerals such as apatite by a process of ion exchange (Faure and Powell 1972; Capo et al. 1997; Bentley 2006).

Stable strontium is composed of four naturally occurring isotopes: ^{88}Sr, ^{87}Sr, ^{86}Sr, and ^{84}Sr, with natural abundances of ~82.74%, ~6.96%, ~9.75%, and ~0.55%, respectively (Slovak and Paytan 2012). Of these, ^{87}Sr is the only radiogenic isotope, with it being formed from the radioactive decay of ^{87}Rb with a half-life of 48.8 billion years (Faure and Powell 1972; Price et al. 2002). The abundance of ^{87}Sr therefore increases throughout geological time (Stueber et al. 1972). Generally, geological $^{87}Sr/^{86}Sr$ ratios fall between 0.700 and 0.750 (Price et al. 2002). It is through the erosion and weathering of rocks that strontium enters soil and water systems, and in turn, the food chain (see Figure 2.1; see Appendix B for more information on strontium within environmental systems).

Strontium enters the food chain when bioavailable strontium in soil is integrated into the matrix of plants and other types of vegetation (Capo et al. 1997). Non-essential elements, such as strontium, can substitute for calcium during nutrient uptake within biological systems (Blum et al. 2000). However, within the body, these non-essential elements are preferentially removed in comparison to calcium (see Appendix B, Section B.6 for more information on strontium in biological systems). Strontium is incorporated into the dental and skeletal tissues of herbivores and omnivores through the consumption of vegetation, while strontium is taken into the tissues

of omnivores and carnivores through the consumption of other animals (Bentley 2006; Slovak and Paytan 2012). Moreover, the $^{87}Sr/^{86}Sr$ ratio measured in skeletal and dental tissues correlate to the concentrated average of dietary strontium that was consumed during life (Capo et al. 1997).

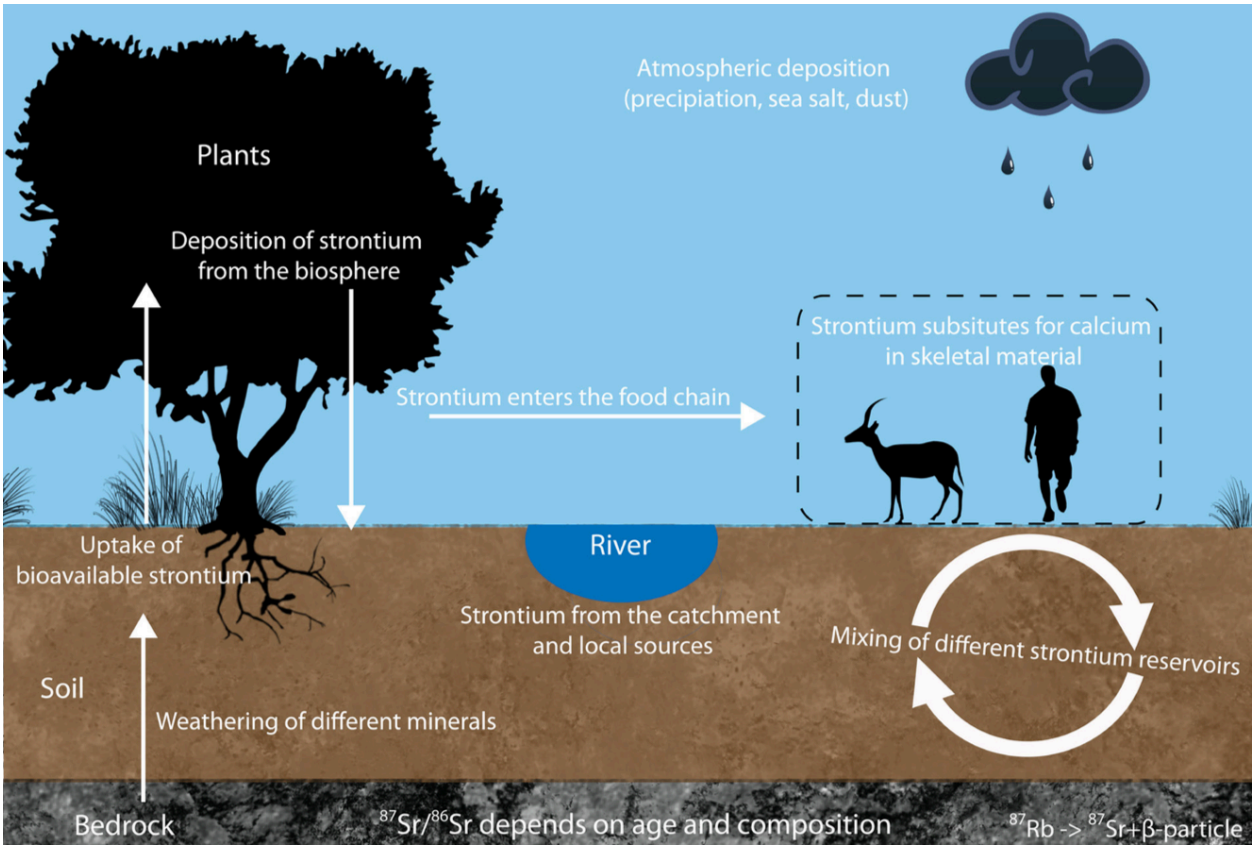

Figure 2.1: "Strontium cycle showing important that affect the strontium composition before it reaches the skeletal material of animals and humans" (borrowed from Willmes 2016, 25).

2.3.b Sampling Biological Hard Tissues for Mobility Studies

Due to their structural differences, tooth enamel and bone can be used for different purposes in strontium isotope studies. Strontium is usually found in concentrations of 50-400 ppm in mature tooth enamel (Hillson 1996; Hewitt 2013). Amelogenesis, the process by which enamel forms, proceeds in two stages: matrix secretion and maturation (Hillson 1996). Tooth enamel begins formation *in utero* and continues after birth with most tooth enamel formation complete by the age of eight (apart from the enamel of the third molar, which is often formed by

age twelve; see Appendix C) (Hillson 2005, 208). Enamel, when mature, is almost entirely inorganic and acelluar, containing 96% inorganic material, less than 1% organic, and the rest water (Hillson 2005). It is for this reason that enamel is relatively unaffected by diagenesis, which is the chemical alteration of biological hard tissues over time through the exchange of elements between the soil and the biological hard tissues themselves (Buikstra et al. 1989; for more information on diagenesis see Section 2.3.e.i). Once formed, dental enamel does not remodel and thus, can provide a permanent record of both the elements and isotopes incorporated into its matrix during childhood formation. Dental enamel has been very useful in determining an individual's origin, as the $^{87}Sr/^{86}Sr$ signatures are likely to match the geological region in which one spent their childhood.

In contrast, bone is made up of a higher percentage of organic material (mostly collagen) and thus can continually incorporate strontium into its matrix throughout life (Sealy et al. 1995). Because trabecular bone remodels at a relatively fast rate and cortical bone remodels more slowly, different skeletal elements fully remodel at different rates (Price et al. 2002). For example, cortical bones such as the diaphyses of the femur and tibia can take decades to remodel, while bones with large amounts of trabecular bone such as ribs can remodel in just a few years (Price et al. 2002). Since bone remodels throughout an individual's lifecourse the $^{87}Sr/^{86}Sr$ signature in bone has the potential to correlate with that of the region in which one lived in approximately the last decade of their life (Price 2002).

2.3.b.i Tooth Development and Laser Ablation

Because this study employs laser ablation it is important to establish a time period in an individual's life in which each ablated line corresponds. Table 2.2 summarizes age estimations of the enamel layers that correspond to each ablated surface, with Line 1 representative of earlier

formed enamel and Line 2 representative of later formed enamel. Ages have been estimated and ranges have been established based upon standards and methods outlined by Anderson et al. (1976), Smith (1991) and Hillson (1995). It is important to note that there is a difference in enamel formation between males and females, with the tooth development of females being further advanced than males on an average of 3% (Hillson 1995, 125). Age estimations have been given based upon this difference between male and female dental development; for individuals who were unable to be identified as male or female the largest possible age range has been estimated to be as conservative as possible. See Appendix C for further information on dental enamel development.

Individual	**Sex Estimation**	**Tooth Sampled**	**Line 1**	**Line 2**
Gu 1	Probable Female	Lower Left Permanent Canine	~3.5 Years	4.0-4.3 Years
Gu 2	Probable Male	Lower Left Permanent Canine	2.9-3.4 Years	4.0-4.8 Years
Gu 3	Possible Male	Lower Left Permanent 2nd Incisor	Roughly after 3 months after birth	4.0-5.0 Years
Gu 4(5)	Indeterminate	Lower Right Deciduous Canine	*In utero*	9.0 months after birth
Gu MISC	Indeterminate	Upper Left Deciduous 1st Molar	Shortly after birth	6.0 months after birth
Gu 7	Possible Male	Lower Right Permanent Canine	Shortly prior to 4.0 Years	4.0-4.8 Years
Gu 8	Probable Male	Upper Left Permanent Canine	~2.5 Years	4.0-4.8 Years
Gu 9	Possible Male	Lower Left Permanent Canine	Shortly prior to 4.0 Years	4.0-4.8 Years
Infant Dc	Indeterminate	Lower Left Deciduous 2nd Incisor	*In utero*	3.0 months after birth
Gu 10	Indeterminate	Upper Left Deciduous Canine	*In utero*	9.0 months after birth

Table 2.2: Age estimations associated with ablated Lines (estimated using Anderson et al. 1976; Smith 1991; Hillson 1996).

$^{87}Sr/^{86}Sr$ ratios in tooth enamel and bone from the same individual can therefore be compared and conclusions can be drawn from either the similarity (i.e. the individual may have spent their early childhood in the same region as they lived) or difference (i.e. the individual may have lived somewhere other than where they were born) observed (see Table 2.3) (Price et al. 2002; Bentley 2006; Hewitt 2013).

	Local Bone Signal	Non-Local Bone Signal
Local Tooth Enamel Signal	The individual lived in the same region throughout their lifetime	The individual lived in the region during enamel formation but lived elsewhere during adulthood or ate primarily non-local foods during adulthood
Non-Local Tooth Enamel Signal	The individual moved into the region some time after enamel formation	The individual lived outside the region throughout their lifetime and either moved shortly before death or was brought to the site after death

Table 2.3: Possible interpretations of isotopic data from bone and tooth enamel (adapted from Table 3.1 of Hewitt 2013, 44).

2.3.c Defining the Local

The value of a local range is defined as two standard deviations from the average $^{87}Sr/^{86}Sr$ ratio in human bones from a site as a whole (Grupe et al. 1997; Price et al. 2002, 2004; Slovak and Paytan 2012; Goude et al. 2012). 'Locals' can be defined as people who either did not move (i.e. grew up and lived in the same region throughout most or all of their lives) or those who moved between similar geochemical regions, whereas the term 'non-locals' refers to "those whose diet catchment extended beyond the local area" (Price et al. 2004, 474).

The formation and remodelling of bone and dental tissues over time along with the simultaneous incorporation of a range of isotopic values due to the ingestion of food and water act as an averaging mechanism for the local $^{87}Sr/^{86}Sr$ variability within the particular region of residence of that animal or human (Price et al. 2002; Montgomery 2010). For example, in their study, Price et al. (2000) demonstrate that $^{87}Sr/^{86}Sr$ values in the local human population at Teotihuacan are identical to those in local rabbit populations (see Figure 3 provided by Price et al. 2002, 125). According to Bentley (2006), small mammals such as mice, rabbits, and squirrels have the lowest within-site variation of $^{87}Sr/^{86}Sr$ with standard deviations no greater than 0.0003 (155). Therefore, because there is the potential for a strong correlation between the $^{87}Sr/^{86}Sr$ ratio in local animal and human populations, it is best to sample small or known local animals so as to ensure that their $^{87}Sr/^{86}Sr$ values are reflective of the region and also to minimize the range of strontium isotope variation (Bentley 2006, 155).

2.3.c.i Mapping $^{87}Sr/^{86}Sr$ in France

A number of scholars, both within (Britton et al. 2009, 2011; Goude et al. 2012; Willmes 2016) and outside (Négrel and Roy 1998; Probst et al. 2000) the sub-discipline of bioarchaeology have employed strontium isotope analyses on datasets and archaeological remains from France. Studies in earth and environmental science have also conducted strontium isotope studies to assess, for example, the chemical composition of rainwaters (Négrel and Roy 1998; Négrel et al. 2007), as well as weathering processes (Probst et al. 2000).

A study conducted by Britton et al. (2009), in the region of France, was the first to look at the variation of intra-tooth strontium and oxygen isotope ratios in modern migratory populations of caribou. Building upon these results, Britton et al. (2011) used the information obtained from migratory populations in order to explore the behaviours and subsistence patterns of Palaeolithic Neanderthal populations. A study by Goude et al. (2012) was the first to use strontium isotope analysis to explore mobility in Neolithic southern France. The scholars measured $^{87}Sr/^{86}Sr$ values in two populations in order to detect outsiders to the region (Goude et al. 2012). For his PhD dissertation, Willmes (2016) established the Isotopic Reconstruction of Human Migration (IRHUM) reference database, which provides the $^{87}Sr/^{86}Sr$ values of plant and soil samples from all major geological regions of France. Through his study, he was able to create the first bioavailable $^{87}Sr/^{86}Sr$ isotope baseline map of France (see Figure 2.2).

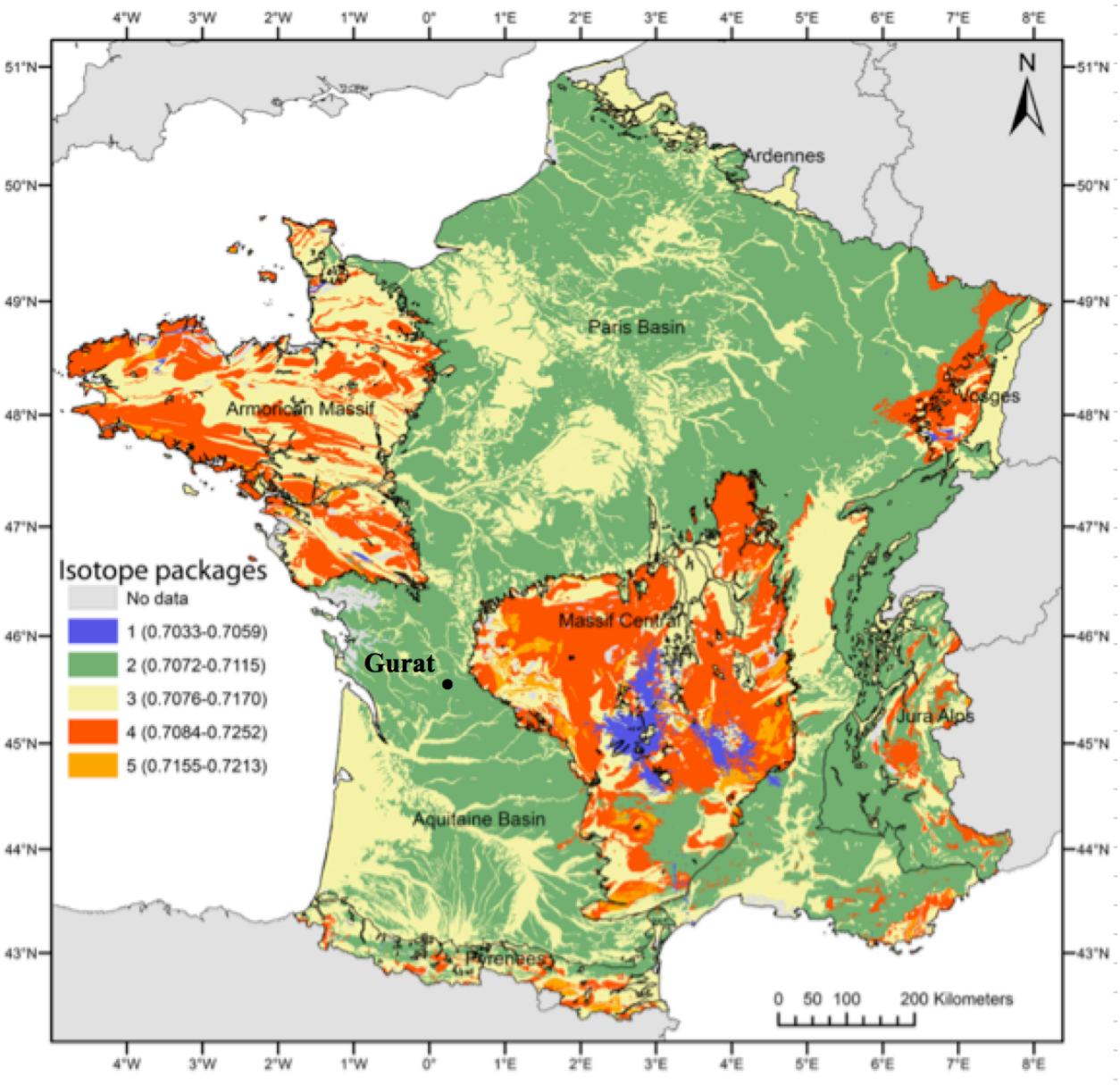

Figure 2.2: Map of the surface geologic lithologies of France, coloured by their classification into the 5 isotope packages (adapted image and title borrowed from Willmes 2016, 60).

Prior to exploring the mobility of the Gurat individuals utilizing Willmes' (2016) isotopic map of France (Figure 2.2), a few limitations and shortcomings must be addressed. The first and foremost limitation that must be noted is that strontium isotope ratios in France form a continuum rather than distinguishable groups (Willmes 2016). This is a potential issue when identifying mobility as distant geographic locations may exhibit similar $^{87}Sr/^{86}Sr$ values due to

their similar underlying geology (e.g. isotope package 2 as shown in green in Figure 2.2). Although isotope packages in Figure 2.2 yield $^{87}Sr/^{86}Sr$ values that overlap significantly, one of most notable differences can be seen between "Isotope Packages 1 and 2" and "Isotope Packages 4 and 5" as the former appears to contain $^{87}Sr/^{86}Sr$ values which correlate to lowland regions and the latter contains $^{87}Sr/^{86}Sr$ values that correlate to highland regions. This map may be used in order to identify broad geographic patterns of mobility, but may not help in distinguishing smaller scale mobility in regions with similar $^{87}Sr/^{86}Sr$ ratios.

As stated by Willmes (2016), this map was created using modern plant and soil samples, which may of issue with regard to archaeological studies as climatological and atmospheric conditions change throughout time and may have had an effect on atmospheric deposition of strontium in the past (Willmes 2016). Willmes (2016) notes it is best to use a combination of resources in conjunction with the map in order to improve the accuracy and reliability of archaeological interpretations.

2.3.d Methodological Approaches

There are a variety of techniques that can be employed in order to conduct strontium isotope analysis, such as bulk sampling and laser ablation. Bulk sampling is a traditional technique used in isotopic studies (Slovak and Paytan 2012). This method involves crushing the sample using a mortar and pestle and the total digestion of that sample in an acid solution. However, the research presented here employs laser ablation multi-collector inductively coupled plasma-mass spectrometry (LA-MC-ICP-MS) in order to both preserve irreplaceable bioarchaeological material and capture snapshots of strontium isotope absorption over time in tooth samples. Unlike bulk sampling techniques, laser ablation is a minimally destructive technique as it does not require the total destruction of a sample material for analysis. Samples

that undergo laser ablation can therefore be used for research purposes more than once. This is important in sampling human remains; as Slovak and Paytan (2012) point out, it is best to be as judicious as possible, preserving the most amount of bone for future analyses.

Laser ablation has the ability to capture retrospective snapshots of isotope and trace element absorption over time in tooth samples, which allows researchers to ask new questions and explore a new type of dataset, one that shows the retrospective indictors of diet, growth, and development (Dolphin 2006). As discussed by Farell et al. (2012), teeth are well suited to bioimagining studies as the laser is able to ablate a preselected surface on a sample that can approach the size of approximately five micrometres (μm) and can correspond to a particular growth band. Thus, laser micro-sampling is ideal if the time-based elemental distribution profiles of dental tissues are of concern to the researcher (Kang et al. 2005). Some additional advantages of laser ablation include direct characterization of solids, no chemical procedures for dissolution and reduced risk of contamination and sample loss (Russo et al. 2001). Although laser ablation allows researchers to explore new research questions as well as preserve samples for future studies, there are limitations that come with its use.

Many scholars have reviewed the accuracy of results produced by laser ablation and drawn comparisons with that of bulk sampling techniques (Copeland et al. 2008; Hewitt 2013). For example, in their study, Copeland et al. (2008) analyzed thirty modern rodent teeth and found a mean difference of 0.0003 ± 0.00002 between $^{87}Sr/^{86}Sr$ measured from laser ablation and by solution analysis. However, this difference is within an acceptable range necessary for mobility studies (Copeland et al. 2008). Additionally, Russo et al. (2001) discuss challenges related to calibration procedures and emphasize the need for homogenous, matrix matched reference materials.

Depending on which laboratory and instrument is used and which isotope or element is chosen for analysis, different standard reference materials must be used in order to calibrate the multi-collector and ensure both the accuracy of the results and the replicability of the study. Standards are necessary as they have known isotopic and/or elemental properties and will optimize the resulting signals. In order to prepare a matrix-matched standard reference material researchers have used pressed powder discs or pellets (e.g. Bellotto and Meikeley 2000), glass standards (e.g. Grupe et al. 1997; Bentley et al. 2003, 2004; Hewitt 2013), and proxy tissues (Lochner et al. 1999).

2.3.e Limitations of Measuring Strontium Isotopes

Although $^{87}Sr/^{86}Sr$ ratios provide an avenue for the exploration of the movement of past populations, there are a number of concerns and limitations that must be addressed. Price and colleagues (2002) address two fundamental issues: 1) a single ratio meant to be representative of local bedrock, soil, and water is difficult to ascertain as values vary across geological landscapes and; 2) it may be difficult to distinguish between locals and non-locals as the $^{87}Sr/^{86}Sr$ ratios vary in human bone and tooth enamel. Additionally, the incorporation of diagenetic strontium into archaeological material must also be given serious consideration (see Appendix E).

The difference between geologically and biologically available strontium must be understood. As discussed by Price and colleagues (2002) bioarchaeologists have used $^{87}Sr/^{86}Sr$ values in bedrock in order to determine local signatures; however, local strontium isotope values from the bedrock are not always directly related to those values found within the local food chain (and are the values seen in human bone and tooth samples). Consequently, biologically available strontium isotope ratios can differ substantially between bedrock, soil, plant, and water values and can be confounded by a variety of environmental and anthropogenic factors. For these

reasons, Sillen et al. (1998) suggest that researchers applying strontium isotope analysis for mobility studies should sample biologically available strontium rather than substrate geology (2466). In order to do this, animal populations can be sampled.

The diet of past individuals and populations can be another confounding factor to consider whilst employing strontium isotope analysis. In order for individual $^{87}Sr/^{86}Sr$ values to be reflective of their location of residence, their dietary uptake must accurately reflect that isotopic value. The consumption of locally grown plants and locally kept animals ensures the accuracy of measuring local $^{87}Sr/^{86}Sr$ values; however, if an individual consumed imported foods, the strontium isotope signatures may not be reflective of their place of origin or residence (Montgomery 2010). The consumption of non-local foods by animals also influences the $^{87}Sr/^{86}Sr$ values that can be measured from animal bones and teeth. For studies on modern populations, this poses as an obstacle and "sever[s] the link between the person and the place of origin" (Montgomery 2010, 332). According to Montgomery (2010), it is assumed in archaeological studies pertaining to sedentary farming communities that past populations were unlikely to sustainably and successfully transport food and water over long distances. However, if food procurement strategies involved fully mobile subsistence or seasonal mobility, then this assumption would not be valid (Montgomery 2010, 332). Additionally, aquatic animals would have an $^{87}Sr/^{86}Sr$ value closer to that of the body of water in which they are found, thus the inclusion of marine food sources must also be given consideration. It is therefore important to assess where the local population under study may have attained their food and water.

2.3.e.i Diagenesis

Diagenesis refers to the chemical alteration of biological hard tissues over time through the exchange of elements between the soil and the biological hard tissues themselves. According

to Buikstra et al. (1989) this alteration depends "upon the structure of the tissue, the environment, diet, physiology, and health status of the living organism" as well as the conditions of the post-mortem depositional environment (169). In reference to elemental composition, diagenesis depends on various factors, which include the climate in which the remains are interred, porosity of the tissue, chemical and isotopic compositions of both biogenic apatite and diagenetic fluid, and water/biomineral ratio (Wang and Cerling 1994, 288). Sillen (1989) points out that diagenesis may not bear a linear relationship to time (212).

Studies by Price (1989), Budd et al. (2000), and Hoppe et al. (2003) suggest that strontium levels in enamel remain fairly stable over time and can be reliable. Due to its high density and low porosity, enamel remains relatively unaffected by diagenesis (Hoppe et al. 2003). Bone, however, is more susceptible to diagenesis as its structure is porous and remodels throughout an individual's life (Price et al. 1992; Budd et al. 2000). Additionally, according to Lambert et al. (1985), strontium appears to be one of the minerals that is least sensitive to diagenesis (476). However, it is advised that pre-treatment protocols be conducted prior to isotopic analysis, especially on bone, as it is more susceptible to diagenesis (Price et al. 1992; Budd et al. 2000; see Appendix E for further information on pre-treatment of bones for isotope analysis).

2.4 Experimental

2.4.a Sample Selection and Preparation

In order to use strontium isotope analysis to explore past residential mobility, both tooth and bone samples were required. One bone sample (N=14) was collected from each of fourteen individuals, whereas tooth samples (N=10) could only be collected from ten of the aforementioned individuals (see Table 2.4). Two faunal bone samples (N=2) were also collected.

During sample collection loose teeth and previously fragmented ribs were given preference so as to ensure the least amount of material was destroyed. Teeth that were not excessively worn and that did not have caries, cracks or discoloration were chosen. Samples were gently cleaned, sonicated in distilled water for 15 minutes and air-dried for 48 hours. Application of pre-treatment was decided against (see Section 2.4.b).

Grave	Individual	Tooth Samples	Bone Samples
Ha	Gu 1	Lower Left Permanent Canine	Rib
Hb	Gu 2	Lower Left Permanent Canine	Rib
	Gu 3	Lower Left Permanent 2nd Incisor	Rib
	Gu 4(5)	Lower Right Deciduous Canine	Rib
	Gu MISC	Upper Left Deciduous 1st Molar	Cranial Frag
Ja	Gu 6	N/A	Rib
	Gu6A	N/A	Long Bone Frag
	Faunal Ja	N/A	Misc. Bone
Dc	Gu 7	Lower Right Permanent Canine	Rib
	Gu 8	Upper Left Permanent Canine	Left Radius
	Gu 9	Lower Left Permanent Canine	Right Fibula
	Infant Dc	Lower Left Deciduous 2nd Incisor	Cranial Frag
	Faunal Dc	N/A	Misc. Bone
Dd	Gu 10	Upper Left Deciduous Canine	Rib
Db	Gu 11	N/A	Rib
	Gu 12	N/A	Rib
Totals	N = 16 Individuals	N = 10 Teeth	N =16 Bones

Table 2.4: Inventory of human and faunal samples.

All twenty-six samples were then transferred into plastic moulds, embedded in resin and left to cure for 48 hours. Samples were cut into thick sections of approximately 1 mm using a Buehler Isomet low-speed saw. Tooth samples were cut longitudinally, from crown to neck, and rib samples were cut transversely to form a cross-section at the mid-shaft. The thick sections were then mounted onto glass slides using Crystalbond adhesive. Each sample was then polished (see Appendix D for polishing procedure), rinsed with distilled water in an ultra-sonic bath for 5 minutes and left to dry overnight. Samples were gently wiped with acetone prior to analyses.

2.4.b Evaluating Sample Integrity

The crystallinity index (CI) of a bone or tooth sample can be used to assess post-mortem changes in bioapatite (Wright and Schwarcz 1996), or diagenesis. The range of CI values in non-

diagenetically altered dental and skeletal material falls between 2.6 and 4.0 (Wright and Schwarcz 1996, 939; Nielsen-Marsh and Hedges 2000; Garvie-Lok et al. 2004; Hewitt 2013). In order to assess the CI value in the bone samples (N=16) collected for this study, Fourier Transform Infrared (FTIR) spectrometry was used.

Based on the reaction to infrared radiation, FTIR monitors the composition and crystal structure of samples. The CI is then determined through the examination of phosphate peaks at 605 and 565 cm^{-1} wavelengths (Wright and Schwarcz 1996, 936) and calculated from the amount of separation between such peaks (Surovell and Stiner 2001, 638). The CI is given by:

$$CI = \{A_{565} + A_{605}\} / A_{595}$$

A_x is the absorbance at wavenumber x (Wright and Schwarcz 1996, 936). Generally, the bioapatite crystals are smaller and less ordered in unaltered bone resulting in a lower CI, while higher CI values are reflective of greater crystallinity and thus suggest that recrystallization has taken place (Shemesh 1990; Wright and Schwarcz 1996, 936; Slovak and Paytan 2012; Hewitt 2013).

Following established methodology for CI measurement, additional <1mg bone samples were ground using an agate mortar and pestle. Analyses were conducted at the Biointerfaces Institute at McMaster University using a Bruker Vertex 70 FT-IR Spectrometer coupled with the Platinum Diamond ATR accessory. Data were reduced using the OPUS 7.2 software package. All samples analyzed yielded crystallinity indices within the acceptable range of 2.6 – 4.0 (N=16, mean = 3.63, SD = 0.1977). Thus, none of the Gurat bone samples were diagenetically altered during the time in which they have been interred, and any resulting LA-MC-ICP-MS measurements of strontium may be viewed as being representative of lifetime origins and mobility.

2.4.c Instrumentation for LA-MC-ICP-MS

In situ strontium isotope analyses were carried out on an Analyte G2 193nm ultra short pulse excimer laser ablation system with a HelEx cell (Photon-machines, Bozeman, MT, USA) coupled to a NuPlasma II multi-collector ICP-MS instrument (Nu Instruments, Wrexham, UK) at the Metal Isotope and Geochemistry Laboratory, University of Waterloo. The operating parameters are summarized in Table 2.5.

Parameters	
MC-ICP-MS	NuPlasma II
RF power	1300
Cool gas flow rate	1.3 L/min
Aux gas flow rate	0.93 L/min
Interface cones	Regular Ni cones for dry plasma condition
Mass resolution	Low
Lens settings	Optimized for signal intensity and peak shape of 88Sr
Collector assignment	H8-88Sr
	H7-87Sr
	H6-86Sr
	H4-85Rb
	H2-84Sr
	Ax-82Kr
Laser ablation system	G2 Analyte
Laser ablation pass	
Scan type	Line
Beam width	50 µm
Translation rate	5 µm/s
Frequency	20 Hz
Fluence	5 J/cm2
Pre-ablation pass	
Scan type	Line
Beam width	65 µm
Translation rate	50 µm/s
Frequency	5 Hz
Fluence	5 J/cm2
Cariier gases	
Helium 1	0.4 L/min
Helium 2	0.2 L/min
Argon	1.4 L/min
Data collection	
Gas background	30 s
Sample	60 s
Integration	0.2 s

Table 2.5: Laser ablation and MC-ICP-MS operating conditions (provided by Liyan Xing, PhD, Department of Earth and Environmental Sciences, University of Waterloo).

2.4.c.i Data Reduction and Analysis

Standard sample bracketing (every 4–5 unknowns) was used and data were normalized to the $^{87}Sr/^{86}Sr$ isotope value of MACS-3 from the USGS with the value of 0.7075532 ± 37 (Jochum et al. 2011). Data were reduced using the Sr isotope CaAr data reduction scheme in the Iolite software package (v. 3.6; Paton et al. 2011), which corrects for ^{87}Rb interference on ^{87}Sr and $^{86}CaAr$ interference on ^{86}Sr. Data are reported with the propagated uncertainty calculated by Iolite. An in-house modern marine shark tooth was used as a secondary standard and yielded a $^{87}Sr/^{86}Sr$ value of 0.70917 ± 2 (N = 27, 2SE), which is in agreement with the $^{87}Sr/^{86}Sr$ value of modern seawater.

2.5 Results

The results of strontium isotope analysis are summarized in Table 2.6 and plotted in Figure 2.3. Two lines were ablated on each tooth sample, with Line 1 (N = 10, mean = 0.7168, SD = 0.0040) representative of earlier formed enamel and Line 2 (N = 10, mean = 0.7169, SD = 0.0047) representative of later formed enamel. With regard to the bone samples, the average of the two ablated lines (N=16, mean = 0.7096, SD = 0.0005) are presented (see Appendix D for individual line values).

2.5.a Bones

All human bone samples have an average $^{87}Sr/^{86}Sr$ value of 0.7096 ± 0.0005 (N=14, 1SD). Since the value of the local range is defined as two standard deviations from the average $^{87}Sr/^{86}Sr$ values in human bones from a site as a whole it is difficult to confidently assign a local range to Gurat as only fourteen individuals are present for this study and many individuals are still interred at the site (Price et al. 2002, 2004). For the purposes of this study, based upon the above definition of the local range, the local $^{87}Sr/^{86}Sr$ range at Gurat can be provisionally

assigned as 0.7085 – 0.7106. The bone values of all fourteen individuals (Gu 1, Gu 2, Gu 3, Gu 4(5), Gu 6, Gu 6A, Infant DC, Gu 7, Gu 8, Gu 9, Gu 10, Gu 11, Gu 12, Gu MISC) fall within this local range. However, one must take care in assuming that this range is truly representative of the local $^{87}Sr/^{86}Sr$ values in Gurat as the sample size is extremely small.

Additionally, Gurat is geographically located in a region in which the geologically available $^{87}Sr/^{86}Sr$ typically ranges from 0.7072 – 0.7115 (Kelly 2009; Willmes 2016). Bone samples taken from two archaeological faunal specimens found buried alongside Gurat individuals yield $^{87}Sr/^{86}Sr$ values that fall within the local strontium isotope range of Gurat (Faunal DC = 0.70945 ± 0.00049 2SE; Faunal Ja = 0.709645 ± 0.000315 2SE). Studies on bioavailable strontium in France are all in agreement with $^{87}Sr/^{86}Sr$ values local to the region in which Gurat is located (i.e. Britton 2011; Evans 2006; Kelly 2009; Voerkelius et al. 2010). All three lines of evidence, human bone $^{87}Sr/^{86}Sr$ values, archaeological faunal bone $^{87}Sr/^{86}Sr$ values, and bioavailable $^{87}Sr/^{86}Sr$ values, are in agreement with the local Gurat value and therefore, it can be suggested with some confidence that the local strontium isotope values in Gurat do indeed fall between 0.7072 – 0.7115. All bone samples have $^{87}Sr/^{86}Sr$ values indicative of the local strontium isotope values for Gurat. None of the bone samples exceed expected ranges for the region.

2.5.b Teeth

The majority of tooth samples have $^{87}Sr/^{86}Sr$ values that are slightly higher than expected for Gurat (>0.7115), which suggests that most of the individuals represented in this study were likely not local to Gurat and thus migrated to this site at some point during their lives.

Sample	Teeth		Bone
	Line 1 (Early)	*Line 2 (Late)*	*Average of Line 1 and 2*
Gu 1	0.71512 ± 0.00081	0.71291 ± 0.00069	0.709755 ± 0.00034
Gu 2	0.71299 ± 0.00095	0.71227 ± 0.00055	0.709065 ± 0.000325
Gu 3	0.71390 ± 0.00230	0.71485 ± 0.00088	0.709385 ± 0.000445
Gu 4(5)	0.71820 ± 0.00170	0.71640 ± 0.00130	0.709065 ± 0.00043
Gu 6	N/A	N/A	0.709565 ± 0.00034
Gu 6A	N/A	N/A	0.709265 ± 0.00034
Infant DC	0.71530 ± 0.00150	0.71580 ± 0.00160	0.709185 ± 0.000435
Gu 7	0.72020 ± 0.00170	0.72040 ± 0.00160	0.70910 ± 0.000575
Gu 8	0.71680 ± 0.00140	0.71910 ± 0.00180	0.71053 ± 0.000425
Gu 9	0.71350 ± 0.00230	0.71140 ± 0.00250	0.710585 ± 0.00052
Gu 10	0.72640 ± 0.00250	0.72720 ± 0.00280	0.70922 ± 0.000425
Gu 11	N/A	N/A	0.70991 ± 0000455
Gu 12	N/A	N/A	0.70914 ± 0.000305
Gu MISC	0.71600 ± 0.00180	0.71920 ± 0.00220	0.71026 ± 0.00049
Faunal DC	N/A	N/A	0.70945 ± 0.00034
Faunal Ja	N/A	N/A	0.709645 ± 0.000315
Mean	0.71684	0.716953	0.70957031
Standard Deviation	0.004016517	0.004734171	0.000510661

Table 2.6: Strontium isotope data ($^{87}Sr/^{86}Sr$) from the Gurat skeletal collection using LA-MC-ICP-MS. All values are given with 2 Standard Error (SE).

The differences between ablated Lines 1 and 2 do not appear to show any form of directionality (which might indicate a patterned travel route or place of origin among individuals). Line 1, representing earlier formed enamel, belonging to seven individuals (Gu 1, Gu 2, Gu 3, Gu Infant DC, Gu 8, Gu 9, Gu MISC) bear $^{87}Sr/^{86}Sr$ values that exceed local Gurat values and correlate to both high and lowland regions in France. Line 1 of tooth samples belonging to two individuals (Gu 4(5), Gu 7) show $^{87}Sr/^{86}Sr$ values that also exceed local Gurat values but correlate only to highland regions in France (e.g. the Massif central). Line 2, representing later formed enamel, belonging to five individuals (Gu 1, Gu 2, Gu 3, Gu 4(5), Gu Infant DC) demonstrates $^{87}Sr/^{86}Sr$ values which correlate to both high and lowland regions in France; Line 2 of tooth samples belonging to three individuals (Gu 7, Gu 8, Gu MISC) show $^{87}Sr/^{86}Sr$ values which correlate only to highland regions in France; Line 2 of the tooth sample belonging to one individual (Gu 9) shows a $^{87}Sr/^{86}Sr$ value that correlates to local Gurat signatures. What this means is that of the ten individuals represented by tooth samples, the two

different ablated Line values (Line 1 and Line 2) of five individuals (Gu 1, Gu 2, Gu 3, Gu Infant DC, Gu 7) do not give $^{87}Sr/^{86}Sr$ values that can be differentiated between isotope packages in France. However, Line 1 and Line 2 ablated from teeth belonging to four individuals (Gu 4(5), Gu 8, Gu 9, Gu MISC) do give $^{87}Sr/^{86}Sr$ values that can be differentiated between different isotopic regions in France. Lastly, the tooth belonging to Gu 10 is interesting in that the $^{87}Sr/^{86}Sr$ value received from both Line 1 (0.72640 ± 0.00250 2SE) and Line 2 (0.72720 ± 0.00280 2SE) are higher than any value representative of France (<0.7252). This may be attributed to standard error, or perhaps this individual spent their childhood outside of France. High $^{87}Sr/^{86}Sr$ values (0.72001 – 0.78000) correspond with values seen in Western Spain, Northwestern Italy and Western Austria (see Figure 1 in Voerkelius et al. 2010). Furthermore, Line 1 ablated from tooth samples belonging to four subadults sampled for this research project (Gu 4(5), Gu MISC, Infant DC, Gu 10) corresponds to enamel layers that were formed *in utero*. What this means is that the $^{87}Sr/^{86}Sr$ value received from Line 1 of the aforementioned teeth indicates maternal mobility. This is because deciduous teeth begin formation *in utero* and thus, the $^{87}Sr/^{86}Sr$ values reflect maternal strontium intake (see Appendix C for information on the tooth formation sequence).

Therefore, one can suggest that many of the individuals were born or originated from a region outside of Gurat. One can also suggest that all individuals sampled for this study lived in or near Gurat for at least the last few years of their lives, long enough for their bodies to exhibit the local strontium signature; this indicates that Gurat may have been regionally significant.

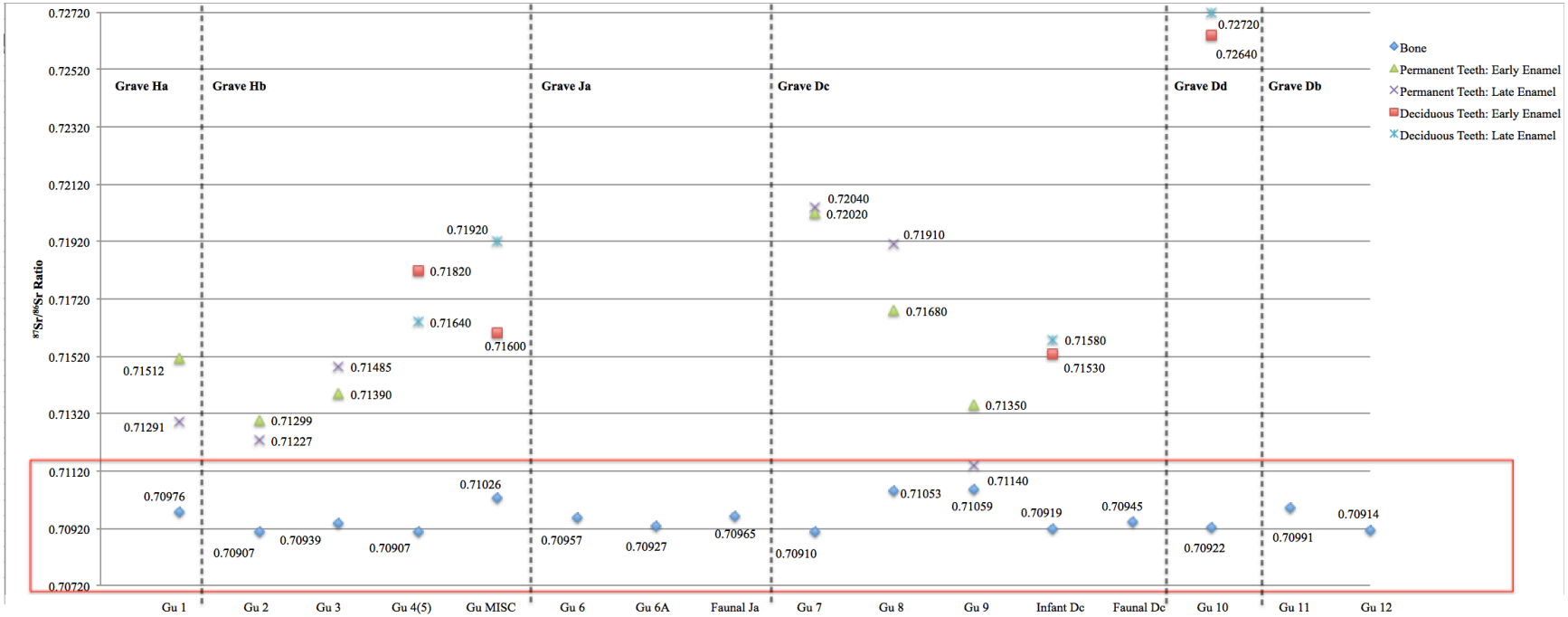

Figure 2.3: Plotted strontium isotope data ($^{87}Sr/^{86}Sr$) from the Gurat skeletal collection where the red box indicates the estimated local strontium isotope range for Gurat (0.7072 – 0.7115) and the black vertical dashed lines separate known graves.

2.6 Discussion

The presence of individuals at Gurat who did not live locally during the first few years of their lives is not surprising. Because two pilgrimage routes traversed the village, it is expected that Gurat was a well-travelled site for non-local Christians during the Middle Ages. What is interesting, however, is that all the individuals buried at Gurat likely lived within the region at least a few years prior to their death, long enough for their bones to exhibit $^{87}Sr/^{86}Sr$ values that match the expected $^{87}Sr/^{86}Sr$ values for Gurat.

Multiple lines of evidence at Gurat suggest that individuals moved throughout the landscape and travelled at least short distances to the site. For example, the pilgrimage route to Santiago de Compostela runs through Gurat, spanning from Vézelay to Bordeaux through to Northwestern Spain (Graham and Murray 1997). It is therefore highly probable that many travelers passed through the village of Gurat. In fact, Santiago de Compostela has continued to be a well-travelled pilgrimage route in present day France and Spain (Graham and Murray 1997). During the High Medieval Ages (1001 – 1300 AD) it was not uncommon for individuals to travel great distances to visit or become part of a religious or monastic order (Stopford 1994; Tierney 1999). According to Graham and Murray (1997) pilgrimage infrastructures such as churches were situated along pilgrimage routes in order to support travelling individuals. It is possible the cave church in Gurat may have represented such an infrastructure at some point during its existence. Additionally, factors such as the bubonic plague, which ravaged the population of Europe and struck France by 1348, and the Wars of Religion, which were fought in France during the sixteenth century, may have also been contributing factors that influenced the decision to stay in or near Gurat during different time periods. Although this preliminary dataset is too small to draw definitive conclusions with regard to the local and regional significance of

the rock-cut cave church in Gurat, this research has revealed that Gurat may have been a site of regional importance.

In addition to medieval pilgrimage routes, transhumance must be given consideration. Transhumance is a form of pastoralism whereby individuals seasonally travel with their livestock. Specifically, in France during the Medieval Ages, Cistercian monks practiced transhumance, moving their livestock to regions located in higher altitudes in the summer (e.g. the Massif Central) and regions located in lower valleys in the winter (Berman 1986; Kibler 1995). Because the majority of tooth enamel $^{87}Sr/^{86}Sr$ values correlate to regions with $^{87}Sr/^{86}Sr$ values similar to that of the Massif Central in France, it seems plausible that the adults may have engaged with transhumance practices. Additionally, this is reinforced with the difference between ablated Lines in the tooth enamel of the four individuals (Gu 4(5), Gu 8, Gu 9, Gu MISC) who can be identified as having migrated from areas not isotopically similar to the region in which Gurat is located.

Because strontium is continually incorporated into bone matrices over an individual's lifetime it is difficult, if not impossible, to identify multiple migrations or particular periods of travel during an individual's adult life. Since different bones remodel at different rates (see Section 2.3.b), in order to further explore seasonal pastoralism, or transhumance, multiple skeletal elements may be sampled and their $^{87}Sr/^{86}Sr$ values compared. For example, in their isotopic study, Hoogewerff et al. (2001) sampled both the femur and rib of "Ötzi the Iceman" in order to explore this individual's movement during life. This is because the diaphysis of the femur can take decades to remodel while ribs remodel in just a few years (Price 2002). Therefore, $^{87}Sr/^{86}Sr$ values as seen in the femur may be indicative of an individual decades prior to their death while ribs reflect $^{87}Sr/^{86}Sr$ values incorporated into their matrix shortly before

death. Sampling multiple skeletal elements may help create a better understanding of the mobility of the Gurat individuals, however in doing so, will further destroy irreplaceable bioarchaeological material.

Due to the small sample size of the dataset and lack of confident sex estimations, it is difficult to make any definitive conclusions with regard to differences between the sexes. The $^{87}Sr/^{86}Sr$ value given by one of the female individuals (Gu 1) is not significantly different from other, male individuals. However Gu 1 is unusual in that, for her age (>50 years), very few pathological changes are displayed on her skeleton: minimal arthritic changes were noted on the vertebral column; no dental caries or abscesses were found; and neither were any traumatic injuries. In contrast, the other seven adults excavated (of which, five are possible males) exhibit extensive pathological changes and traumatic injuries (see Appendix A). Additionally, if the women present at Gurat were in fact active participants in religious activities (i.e. nuns) this may shed light upon when this cave church was inhabited. It is likely that all the individuals buried at Gurat were indeed participants in the religious community; after the tenth century the churchyard was established as the sole burial place for the parish community (Zadora-Rio 2003). According to Tierney (1999), during the twelfth century new religious movements, such as the Cistercian reforms, facilitated a shift in the attitude towards women and thus women began to participate more actively within religious settings.

It is important to keep in mind, however, that the individuals sampled for this study may not be representative of all the individuals buried at Gurat. It is not known at this time exactly how many individuals are still interred. It is also not known exactly what time period all of the individuals at Gurat were buried. As previously discussed, it seems likely that these individuals were all buried within the span of a few centuries (likely between the thirteenth and sixteenth

centuries; see Section 2.2); analysis of mobility does not appear to give insight into the time periods in which each individual likely lived and died in Gurat.

The consumption of marine resources may increase the strontium isotope signature in biological hard tissues due to the homogenous $^{87}Sr/^{86}Sr$ value of the ocean and marine life. It is likely that the individuals at Gurat, however, were not consuming marine resources because 1) Gurat is located inland, and, if they were indeed monastic, 2) hermits and monks during the early and high Middle Ages drastically limited their food intake, consuming items such as bread, milk, cheese, water and wine (Tierney 1999, 299). Thus, it can be assumed that the $^{87}Sr/^{86}Sr$ value as reflected in the skeletal remains of the Gurat individuals were not influenced by non-local foods.

Although it is tempting to assume that all the individuals lived in or near Gurat during the final years of their lives, one must keep in mind that strontium isotope values in France are largely homogenous to the North, South and West of the region under study.

2.7 Suggestions for Future Research

The preliminary data presented here have demonstrated that strontium isotope analysis can identify the origins and mobility of the Gurat individuals and thus, give insight into the regional importance of the rock-cut cave church. However, more archaeological human samples are required in order to further explore and test the hypothesis that Gurat held regional significance. It would be beneficial to continue excavations at the cave church in order to gain a better understanding of the individuals that dwelled in Gurat. In order to make definitive conclusions the sample size must be increased, and as result, patterns can be explored. Further mobility studies should also be tested in order to further reinforce the findings of this study. Oxygen isotope analysis would compliment the discussion on the origins and mobility of the Gurat individuals.

Further exploration into neighbouring rock-cut cave church sites may also help to enhance knowledge with regard to medieval monastic life. The lack of research on medieval cave dwelling individuals makes any definitive conclusions with regard to the importance of Gurat difficult. Future studies not only using strontium isotope analysis will provide valuable information that can be used to help identify the purpose and meaning of other cave dwelling sites that extend beyond the scope of southwestern France.

It would also prove fruitful to explore alternatives to destructive analytical techniques in order to preserve irreplaceable biological and archaeological material. Alternative techniques to traditional solution work, such as laser ablation, not only provide the opportunity to preserve bioarchaeological material but also provide researchers with new sets of questions and yield additional types of datasets.

2.8 Concluding Remarks

This study has used strontium isotope analysis in order to explore the origins and explore the mobility of the medieval monastic individuals buried at the rock-cut cave in Gurat, France. It has been identified that most of the individuals represented in this study may be non-local to Gurat – being born in a region other than the one in which they lived the last few years of their lives. It is not known at this time exactly when the individuals may have migrated to Gurat, nor is it clear the motivation behind their mobility. Strontium isotope ratios of archaeological teeth and bone, as well as of archaeological fauna, from graves located just outside and to the East of the cave church entrance in Gurat have provided valuable information with regard to the regional influence of this cave church, and if coupled with archaeological and historical lines of evidence, may facilitate exploration of medieval monastic life.

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APPENDIX A: Osteobiography

The Gurat Skeletal Collection: An Osteobiography Conducted Using Standards Outlined by Buikstra and Ubelaker (1994)

A.1 Section H

Two graves were found in Section H: Grave Ha and Hb

A.1.a Grave Ha

Grave Ha was a small grave, which contained the remains of two adults (Gu 1 and Gu 1A). This grave was located between the apse and entrance of the cave church (Clements and Gruspier n.d.).

Gu 1

Gu 1 was found in a primary burial, buried with their back to the ground, legs extended and arms, flexed, raised above their head. This individual was oriented toward the east, in an orientation toward the Winter solstice. Gu 1 is estimated to be a female age 50+ years at death. Age estimations are based upon cranial suture closure and the auricular surface of the ilium. Both the skull and pelvis were used in order to estimate sex. Gu 1 is surprising in that their teeth do not show dental wear that may be associated with an individual of this age. Neither dental caries nor periodontal disease is present. Periostitis was found on the distal portion of the tibiae.

Gu 1A

Gu 1A was not sampled for this research project. Two portions of temporal bone were found with Gu 1, which could not belong to Gu 1, as a complete skull was present. Gu 1A represents an adult (Clements and Gruspier n.d.).

A.1.b Grave Hb

Grave Hb was a large central cavity, which contained the remains of five individuals (Gu 2, Gu 3, Gu 4(5), Gu MISC, and a miscellaneous adult). It was also located between the apse and

entrance of the cave church (Clements and Gruspier n.d.). All the individuals were found buried at a depth of sixty centimetres.

Gu 2

Gu 2 was found in a primary burial, oriented in a similar fashion as Gu 1. Gu 2 was buried in a separate stone enclosure at the south side of grave Hb. The skeletal remains of Gu 2 are very robust; it is estimated that they were a male between the ages of 35 and 50 years at death. Age estimations are based upon cranial suture closure and the auricular surface of the ilium. Both the skull and pelvis were used in order to estimate sex. Arthritis is very pronounced on the lumbar vertebrae (particularly L1 and L2). Trauma was also noted: healed fractures on the right metacarpal, right twelfth rib, left talus and spinous process of the sixth cervical vertebrae. Extensive alveolar resorption and extreme dental wear was also noted.

Gu 3

Gu 3 was found in a primary burial, found with their back to the ground, legs extended and arms, flexed and raised above their head. Orientation indicates that this individual was perhaps buried during the summer solstice, as all burials were positioned east – facing the rising sun (Clements and Gruspier n.d.). Gu 3 is estimated to be a possible male age 20-35 years at death. Age estimations are based upon cranial suture closure. The skull and limited evidence on the pelvis were used in order to estimate sex. Various pathological changes have been regarded on this individual. The coronal suture appears to have been prematurely fused (the frontal appears flat while the posterior part of the skull appears bulbous). Extreme alveolar resorption is noted, as well as ante-mortem loss of most mandibular molars.

Gu 4(5)

Gu 4(5) was found in a primary burial, buried in the fetal position on their left side, with an orientation that matched Gu 3. The excavators initially believed that Gu 4(5) was two individuals, hence the labelled of 4(5). Gu 4(5) is a subadult, age 4 years ± 12 months at death, estimation based on dental eruption and epiphyseal fusion. This individual is badly fragmented and no pathology has been noted on their remains.

Gu MISC

Gu MISC is represented by one deciduous left first molar, estimated to have been 6 years ± 24 months at death. Gu MISC is also represented by one juvenile bone fragment.

Miscellaneous Bone

Found alongside Gu MISC were three adult occipital bone fragments. These bones were not sampled for this project.

A.2 Section J

One grave was found in Section J: Grave Ja.

A.2.a Grave Ja

Grave Ja is a small grave found alongside grave Ha. This grave contained the skeletal remains of two individuals (Gu 6 and Gu 6A).

Gu 6

Gu 6 was found disturbed upon excavation, with a burial depth of only thirty-five centimeters (much shallower than the previously excavated individuals). This individual was lying on its back with legs extended and arms being crossed over the chest, which also differed from previously excavated individuals. Because the feet were found to be touching, Gervers

(1968) suggests that this individual may have been wrapped at the time of burial. Gu 6 was oriented northeast, which differed slightly from all other individuals excavated.

This individual is determined to be female based solely on pelvic morphology (as the skull was not present for analyses), with age at death being between 14 and 16 years. Age was estimated based upon pubic symphysis morphology and examination of the auricular surface. One Schmorl's node was found on each of two lumbar vertebrae. No teeth were available for study, and ribs and vertebrae were limited; the skull was highly fragmented. Gu 6 was found buried with a few infant bone fragments (see Gu 6A).

Gu 6A

Gu 6A was located alongside Gu 6 and is only represented by ~10 bone fragments. It is arbitrarily estimated that Gu 6A was birth to 3 years of age at death given the examination of the postcranial skeleton.

A.3 Section D

Three graves were found in Section D: Grave Dc, Dd and Db.

A.3.a Grave Dc

Grave Dc contained a multiple burial with five individuals present: Gu 7, Gu 8, Gu 9, Infant Dc and an additional individual. The additional individual was an adult being represented by only a few fragments, including a portion of a left tibia, which displays periostitis.

Gu 7

Within grave Dc, Gu 7 was the only fully articulated individual; Gu 7 was lying on their back, legs extended and arms flexed across the chest. This individual is a possible male and aged to be between 35 – 50 years at death. Sex estimation is based upon the examination of the skull

and the pelvis, and the examination of cranial suture closure along with public symphysis morphology and auricular surface aging were used in order to estimate age at death.

Eburnation and lipping is noted on the vertebral bodies and sacrum. Schmorl's nodes are also present on the vertebral bodies. One midshaft rib fragment displays a healed fracture. Alveolar resorption is noted in both the maxilla mandible. Extensive dental caries can be seen on canines, premolars and molars.

Gu 8

Gu 8 is laid directly on top of Gu 9. This individual is aged to be 35 – 50 years at death and is determined to be a probable male. Age estimation is based upon cranial suture closure and auricular surface aging, and sex was estimated based upon examination of cranial features as well as the preuaricular sulcus. No mandibular teeth are present. Gu 8 is mostly represented by the appendicular skeleton and skull. Ribs are present but it is unclear as to whether they belong to Gu 8 or Gu 9. The hands and feet are not present.

Gu 9

Gu 9 was found intermingled with the remains of Gu 8. This individual is aged to be 35 – 50 years at death. Age at death was estimated based upon cranial suture closure and examination of the auricular surface. Based upon pelvic morphology and cranial features, this individual is estimated to be a probable male. No maxillary teeth are present. Mandibular teeth (right canine, first left incisor, left canine and first left premolar) exhibit extensive wear. The hands and feet are not present and neither are the facial bones.

The first cervical vertebra is fused to the occipital condyles at the base of the skull. The twelfth thoracic vertebrae, and first, second and third lumbar vertebrae display healed fractures on their bodies, as well as pitting and lipping, and osteophyte formation. The fourth lumbar

vertebra displays pitting and osteophyte formation. The sacrum also exhibits healed fractures along its body (likely compression fractures). Arthritis is also displayed on the superior and inferior aspects of the vertebral bodies aforementioned. The left pelvic ischial tuberosity also exhibits a healed fracture (fracture appears to run vertically, through the medial portion of the bone). Both acetabula appear to show arthritic deformation, with the presence of lipping and pitting. Clements and Gruspier n.d. suggest that these fracture patterns are possibly indicative of a fall from height.

Infant Dc

Infant Dc was not articulated, only represented by roughly 8 bone fragments (including fragments of cranial bone and long bone). The lower left deciduous second incisor is present. This individual was aged to be 4 months ± 2 months.

A.3.b Grave Dd

Little information is given on Grave Dd. It was thought to have been a secondary burial, as skeletal material was highly disturbed. Stone from the wall of the apse was found in the grave – perhaps being destroyed during the War of Religion (Clements and Gruspier n.d.).

Gu 10

Gu 10 was aged to be 3 years ± 12 months based upon dental eruption and epiphyseal fusion. This individual was highly fragmented; vertebrae are not present, neither is the pelvis. Two loose teeth are present: upper left deciduous canine and lower left deciduous canine.

A.3.c Grave Db

The remains of two individuals were found in Grave Db: Gu 11 and Gu 12. Their remains were disarticulated, which Clements and Gruspier n.d. suggest is indicative of a secondary burial.

Gu 11

Gu 11 was aged to be 35 – 50 years at death based upon limited evidence of the postcranial skeleton (i.e. auricular surface aging). Although an acute left great sciatic notch is present, the sex of this individual is unable to be determined due to lack of additional evidence. Slight arthritic change was noted on the thoracic vertebral bodies, as well as osteophyte formation. The left acetabulum exhibits some lipping. No teeth are present.

Gu 12

Gu 12 was aged to be 20 – 35 years at death based upon limited evidence of the postcranial skeleton. Not enough evidence was available for accurate sex estimation. The fragmentary remains present are, however, gracile in nature. No pathological changes or traumatic injuries are noted.

APPENDIX B: Strontium in Environmental Systems

B.1 Strontium in the Environment

Within environmental systems strontium can be found in rivers, oceans, soils, and plants, and are incorporated into each in different ways. Primarily, strontium is found in rocks and when released by weathering or erosion, moves into soil, surface water and groundwater, which facilitate its spread into the food chain (see figure 1). It is important to note that $^{87}Sr/^{86}Sr$ ratios in rocks are likely heterogeneous as rocks can be made up of different minerals (Beard and Johnson 2000). Strontium is also dispersed into soil and waterways through precipitation and sea-spray. Geologists were the first to explore the environmental variation of strontium isotopes in order to date igneous and sedimentary rocks (i.e. Wickman 1948). Archaeologists now exploit the isotopic variation of strontium in order to explore patterns in animal and human mobility.

Due to the large atomic mass of strontium (and the small differences in relative mass between strontium isotopes) its isotopic composition is not changed, or fractionated, by biological processes (Bentley 2006, 141). This is important in strontium isotope analysis as, according to Bentley et al. (2002), the strontium compositions of bone and tooth samples match the diet of past individuals, which in turn have the potential to reflect the strontium isotope composition of the local geology (see section 4.2). These ratios can serve as a means to trace animal and human migration by matching $^{87}Sr/^{86}Sr$ ratios of the bone and tooth samples to that of the geological and environmental landscape.

B.2 Strontium in Geological Landscapes

The ratio of $^{87}Sr/^{86}Sr$ in a rock mineral depends on three factors: the amount of strontium and rubidium at the time the rock crystalized, the $^{87}Rb/^{86}Sr$ ratio (which is directly proportional to the Rb/Sr), and the time elapsed since formation (Bentley 2006, 137).

Strontium is found in 0.02-0.03% of the earth's crust (Nielsen 2004). $^{87}Sr/^{86}Sr$ ratios vary substantially throughout geological terrains due to the geochemical differences between rubidium and strontium. Very old rocks (>100 mya) that had high original Rb/Sr ratios will have high $^{87}Sr/^{86}Sr$ ratios (above 0.710), whereas geologically young rocks (<1-10 mya) that initially had low Rb/Sr ratios will have lower $^{87}Sr/^{86}Sr$ ratios (less than 0.704) (Bentley 2006, 139). It is through the erosion and weathering of rocks that strontium enters soil and water systems, and in turn, the food chain.

B.3 Strontium in Soils

Through environmental processes and anthropogenic activity, soil can exhibit a range of $^{87}Sr/^{86}Sr$ values. Environmental processes such as mineral weathering, movement of water systems, and atmospheric deposition, as well as anthropogenic activity such as the use of fertilizers can influence the strontium isotopic values in soil, plants, and thus in animals and humans. There are three parts to soil: the bioavailable fraction, carbonate fraction and silicate fraction (Willmes 2016). Strontium is incorporated into each; however, the bioavailable portion is the only fraction in which plants can uptake strontium (Sillen et al. 1998).

The strontium concentration in soil typically ranges from 0.2 to 20 ppm (Miller et al. 1993; Capo et al. 1997; Bentley 2006). Depending on the location of a region and its climate, mineral bedrock weathering generally contributes most significantly to strontium values in soils, however surface and groundwater as well as atmospheric deposition, which includes sea-spray, precipitation, and dust, can contribute to the amount of strontium within soils (Capo et al. 1997; Bentley 2006; Slovak and Paytan 2012).

Sea-spray can affect the strontium isotope values in coastal areas (Bentley 2006). In their study, Whipkey et al. (2000) examined the strontium isotopic values in sea-spray in soil from a

site 50 meters off the Pacific Coast of Hawaii. They found that carbonate buried within the soils from this site contained up to 50% of $^{87}Sr/^{86}Sr$ values indicative of marine sources (Whipkey et al. 2000, 46). Whipkey et al. (2000) contrasted their findings to that of Capo et al. (1997), who found that semiarid sites located within inland Hawaii were dominated by the strontium values of weathering of bedrock. These studies demonstrate that $^{87}Sr/^{86}Sr$ values within soils from coastal regions are predominately affected by marine sources, like sea-spray, whereas inland soils typically have $^{87}Sr/^{86}Sr$ values that similar to that of the local bedrock.

Although strontium concentrations in rainfall are typically less than 0.001 ppm they can be an influential contributor to environmental $^{87}Sr/^{86}Sr$ values (Capo et al. 1997, 207). Strontium isotope ratios in precipitation vary depending on location and can be affected by nearby bodies of water and locally derived dust, called loess (Capo et al. 1997; Bentley 2006). In regions with high annual levels of rainfall, the $^{87}Sr/^{86}Sr$ values in soil are more closely correlated to those of the precipitation than bedrock weathering (i.e. Vitousek et al. 1999). In contrast, soils in regions with low annual levels of precipitation will exhibit $^{87}Sr/^{86}Sr$ signatures dominated by bedrock weathering (Sillen et al. 1998; Bentley 2006; Willmes 2016). The isotopic values in precipitation can have an effect on the strontium available to plants, and thus both animals and humans. For example, Vitousek et al. (1999) conducted a study that examined the effect of precipitation on $^{87}Sr/^{86}Sr$ values in 34 different Hawaiian forests. The scholars concluded that annual precipitation was the best indicator of strontium isotope ratios, with precipitation accounting for 56% of the total variation of strontium isotopes in trees (Vitousek et al. 1999, 257). Precipitation is therefore one of many environmental contributors of strontium to soils and plants.

The depth of the soil impacts the atmospheric contribution of strontium; as depth increases atmospheric contributors become less important while the weathering of bedrock

significantly contributes to the isotopic signal (Prohaska et al. 2005; Bentley 2006). Loess is a major contributor of strontium in soils within drier climates, especially in soils that are closer to the earth's surface (Bentley 2006, 150). For example, Prohaska et al. (2005) conducted a study on the isotopic composition of soil along a depth profile of up to 120cm. In particular, they found that atmospheric contributors such as loess impacted the $^{87}Sr/^{86}Sr$ values within the topsoil (~10cm in depth), which reflected an isotopic value of 0.718 (Prohaska et al. 2005, 246). As depth increased, the ratio of $^{87}Sr/^{86}Sr$ more closely correlated with that of bedrock values, being 0.715 (Prohaska et al. 2005, 246). Thus, the depth at which soil is sampled can impact bioarchaeological research and the understanding of a 'local' $^{87}Sr/^{86}Sr$ range.

B.4 Strontium in Surface and Ground Water

Through erosion, strontium enters surface waters such as rivers, streams, lakes and oceans. Strontium also enters groundwater through erosion. In rivers, the concentration of strontium varies from 0.006 to 0.8 ppm, averaging at 0.06 ppm (Capo et al. 1997; Bentley 2006, 143) and its isotopic composition is reflective of bedrock weathering and atmospheric inputs (Capo et al. 1997, 204). Elevated regions erode faster than low plains and therefore have an effect on the isotopic composition of the river sediments. Because rivers at low elevations tend to carry a mix of upstream rocks, soils, and precipitation, the $^{87}Sr/^{86}Sr$ ratio is less reflective of the underlying bedrock whereas the $^{87}Sr/^{86}Sr$ ratio of rivers at high elevations is more closely correlated to that of the regional bedrock (Bentley 2006). As Bentley (2006) notes, river composition is often representative of the $^{87}Sr/^{86}Sr$ available to soils and plants (144).

Unlike rivers and streams, the $^{87}Sr/^{86}Sr$ ratios in oceans are generally homogenous at any given time and represent the entire global average of weathered continental crusts (Bentley 2006, 146). This is due to the several million-year residence time of strontium in oceans and the

ocean's turnover rate of a few thousand years (Capo et al. 1997, 205; Bentley 2006, 147). According to Bentley (2006) the $^{87}Sr/^{86}Sr$ ratio of ocean water is currently 0.7092, but has varied over geologic time between 0.707 and 0.709 (146). Within ocean systems, sedimentary rocks reflect the $^{87}Sr/^{86}Sr$ ratios of their original geological sources, whereas shells and carbonates reflect the $^{87}Sr/^{86}Sr$ ratio of the ocean water during the time of their formation.

In contrast to surface waters, the $^{87}Sr/^{86}Sr$ values in groundwater are impacted less by atmospheric input and more by bedrock erosion and thus, may be more closely correlated to the underlying geology (Willmes 2016). Willmes (2016) states that anthropogenic activity such as agriculture may influence the strontium isotope ratio in groundwater samples.

B.5 Anthropogenic Influence on Strontium Isotope Values

More recently, fertilizers have had an impact on the strontium concentrations and isotopic signatures found within water and soils and, consequently, affect the uptake of strontium in animal and human populations. Many scholars have studied the effects of fertilizers (i.e. Böhlke and Horan 2000; Vitòria et al. 2004; Frei and Frei 2013) and other anthropogenic contamination like pollution (i.e. Maurer et al. 2012) on the strontium isotope values in soils. In their study on the coastal plain of Maryland, Böhlke and Horan (2000) found that prior to the introduction of fertilizers, marine carbonates had a $^{87}Sr/^{86}Sr$ of ~0.708, and since, groundwater $^{87}Sr/^{86}Sr$ ratios have risen to ~0.713-0.715 (604). Anthropogenic activities must be taken into account when comparing archaeological and present data (Slovak and Paytan 2012).

Overall, isotopic signals for strontium in soils and water systems vary, being dependent upon geological landscapes, environmental processes, and the anthropogenic activities that take place within a region.

B.6 Biopurification (Strontium in Biological Systems)

Calcium is a vital component to many biological and biogeochemical processes (Blum et al. 2000). Non-essential elements, such as strontium, tend to substitute for calcium as trace constituents during nutrient uptake (Blum et al. 2000). However, within the body, these non-essential elements are preferentially removed in comparison to calcium, thus creating a decrease between the Sr/Ca ratio (with 10-40% of strontium and 40-80% of calcium being absorbed by the body of a mammal) (Blum et al. 2000; Bentley 2006, 154; Willmes 2016, 32). Additionally, the Sr/Ca ratio also decreases as the trophic level increases (Blum et al. 2000; Bentley 2006). The reduction of Sr/Ca is a factor of five per trophic level: the Sr/Ca in plants is roughly 20% of that in their soils, the Sr/Ca in the skeletal tissues of herbivores is roughly 20% of the average of the plants consumed, and the Sr/Ca in carnivore skeletal tissues is 20% of that in the herbivores consumed (Bentley 2006, 154). In their study, Burton et al. (1999) measured over 1000 samples of soil, water, vegetation, and both animal and human bones in order to assess the process of biopurification between the ratios Sr/Ca and Ba/Ca. They found ranges of ±0.09940 for Sr/Ca in soils, ±0.00957 in plants, ±0.00090 in herbivore skeletons, and ±0.00039 in carnivore skeletons (Burton et al. 1999; Price 2002; Bentley 2006). These results show the decrease in variability between the Sr/Ca ratios ascending through trophic levels.

Strontium isotopes are also affected in a similar way through the process of biopurification. The $^{87}Sr/^{86}Sr$ in animal dental and skeletal tissues is reduced from that of the plants and soils; carnivores typically have the smallest standard deviation of $^{87}Sr/^{86}Sr$ (Blum et al. 2000; Bentley 2006).

APPENDIX C: Dental Enamel Development

C.2 Dental Enamel

The human tooth is made up of enamel, dentin, cementum, and pulp. Enamel, when mature, is almost entirely inorganic and acelluar (Hillson 2005). Once formed, dental enamel provides a permanent record of trace elements and isotopes that are incorporated into its matrix during childhood formation.

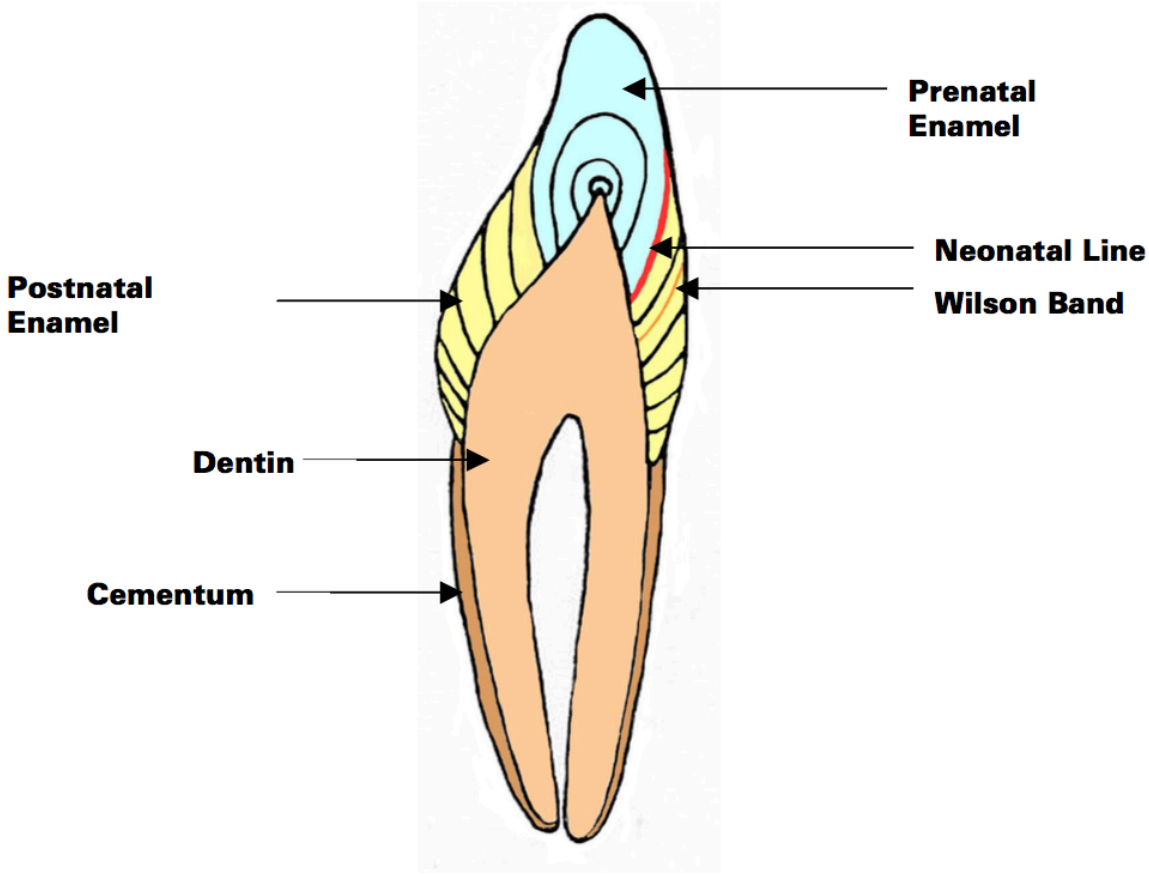

Figure C.1: Illustration of a longitudinally sectioned deciduous incisor showing dental tissues, pattern of enamel development, and histological features (title and image borrowed from Dolphin 2006, 104).

Enamel is formed by ameloblasts, which are narrow and packed together between the dentine and the outer surface of the tooth. Amelogenesis, or enamel formation, progresses in two stages: matrix secretion, and maturation (Hillson 1996). Matrix secretion involves the formation

of an organic matrix and it is during this phase that apatite crystallites are seeded into the matrix (Hillson 2005). At this stage the matrix is one third mineral, one third protein and one third water. Throughout the second phase of development, maturation, heavily mineralized mature enamel forms due to the removal of protein and water from the matrix (Hillson 1996). Ameloblasts in different areas begin mineralization at different times: those at the coronal tip of the crown begin first, followed by those down the crown sides, with the ameloblasts at the cervix beginning last (Hillson 2005). Because this process is progressive, different teeth can record different life stages (Humphrey et al. 2007).

There are a number of incremental lines and pathological bands that can be seen on enamel both macroscopically and microscopically that should be given consideration. Brown striae of Retzius are incremental growth bands that can be seen on the surface of enamel. The neonatal line is the first striae of Retzius and appears on deciduous teeth and the first permanent molars because as they develop *in utero* (FitzGerald and Saunders 1997). According to Hillson (1997), the prominence of this line may depend on the circumstances at birth.

Additionally, some pathological bands can occur in enamel, affecting the mineralization process. Wilson bands and enamel hypoplasias are accentuated lines seen within the enamel – they occur due to the disruption of the ameloblasts during the matrix secretion and maturation phases. Goodman and Rose (1990) define enamel hypoplasias as deficiencies in the enamel thickness due to physiological stress during amelogenesis. Stress (e.g. malnutrition, illness) disrupts the rate at which the ameloblasts mineralize the enamel causing visible accentuated line in teeth. These deficiencies can be used as non-specific stress indicators, and since enamel does not remodel, these defects can be used as a retrospective indicator of stress during tooth crown formation (Goodman and Rose 1990; Hillson and Bond 1997).

C.3 Tooth Formation Sequence

C.3.a *In Utero* Tooth Formation

Tooth formation begins *in utero* with the deciduous incisors, the first forming between 14-18 weeks and the second forming at about 16-18 weeks after fertilization (Hillson 1996). The deciduous canine then begins formation about a week after the incisors begin (Smith 1991). Deciduous first molars and second molars begin formation at about 15 weeks and 18-19 weeks, respectively (Hillson 1996). The only permanent dentition to form *in utero* are the first molars, which initiate at about 28-32 weeks (Hillson 1996).

C.3.b Postnatal Tooth Formation

After birth, the permanent first incisors and lower second incisors begin formation at about 3-4 months of age (Hillson 1996). The permanent upper second incisors begin formation at the end of the first year (Hillson 1996). The permanent canines begin formation about 4-5 months of age (Hillson 1996). Following into the second and third year, the first and second premolars begin formation as well as the permanent second molar. The crown of the permanent first molar, which began formation *in utero*, completes at about 3 years of age (Hillson 1996). Crown formation is compete at about 4-5 years of age for the permanent incisors; about 6 years of age for the permanent canines and first premolars and; 7 years of age for the second premolars and permanent second molars (Hillson 1996, 2005).

APPENDIX D: Methodology and Raw Data

Methodology and Raw Data Collected from Both Strontium Isotope Analysis Employing Laser Ablation Multi-Collector Inductively Coupled Plasma-Mass Spectrometry (LA-MC-ICP-MS) and Fourier Transform Infrared (FTIR) Spectrometry

D.1 Methodology

D.1.a Polishing Procedure

Each sample was polished for 2 minutes on a polishing pad with 800 grit, for 3 minutes on a polishing pad with 1000 grit, for 3 minutes on a polishing pad with 2000 grit, for 3 minutes in Micro Metallurgical Silicon Carbide Powder with 600 grit and for 3 minutes in Micro Metallurgical Silicon Carbide Powder with 1000 grit. In between each polishing session samples were rinsed with distilled water in an ultra-sonic bath for 2 minutes. After polishing was complete, samples were rinsed with distilled water in an ultra-sonic bath for 5 minutes and left to dry overnight. Samples were gently wiped with acetone prior to analyses.

D.2 Data Received from LA-MC-ICP-MS

Sample	**Teeth**		**Bone**	
	Line 1	*Line 2*	*Line 1*	*Line 2*
Gu 1	0.71512 ± 0.00081	0.71291 ± 0.00069	0.70938 ± 0.00033	0.71013 ± 0.00035
Gu 2	0.71299 ± 0.00095	0.71227 ± 0.00055	0.70890 ± 0.00034	0.70923 ± 0.00031
Gu 3	0.71390 ± 0.00230	0.71485 ± 0.00088	0.70944 ± 0.00048	0.70933 ± 0.00041
Gu 4(5)	0.71820 ± 0.00170	0.71640 ± 0.00130	0.70889 ± 0.00042	0.70924 ± 0.00044
Gu 6	N/A	N/A	0.70952 ± 0.00036	0.70961 ± 0.00032
Gu 6A	N/A	N/A	0.70937 ± 0.00033	0.70916 ± 0.00035
Infant DC	0.71530 ± 0.00150	0.71580 ± 0.00160	0.70926 ± 0.00038	0.70911 ± 0.00049
Gu 7	0.72020 ± 0.00170	0.72040 ± 0.00160	0.70894 ± 0.00076	0.70926 ± 0.00039
Gu 8	0.71680 ± 0.00140	0.71910 ± 0.00180	0.71027 ± 0.00037	0.71079 ± 0.00048
Gu 9	0.71350 ± 0.00230	0.71140 ± 0.00250	0.71066 ± 0.00060	0.71051 ± 0.00044
Gu 10	0.72640 ± 0.00250	0.72720 ± 0.00280	0.70900 ± 0.00049	0.70944 ± 0.00036
Gu 11	N/A	N/A	0.70960 ± 0.00049	0.71022 ± 0.00042
Gu 12	N/A	N/A	0.70907 ± 0.00032	0.70921 ± 0.00029
Gu MISC	0.71600 ± 0.00180	0.71920 ± 0.00220	0.70976 ± 0.00050	0.71076 ± 0.00048
Faunal DC	N/A	N/A	0.70952 ± 0.00032	0.70938 ± 0.00036
Faunal Ja	N/A	N/A	0.70963 ± 0.00034	0.70966 ± 0.00029

Table D.1: Raw strontium isotope data ($^{87}Sr/^{86}Sr$) from the Gurat skeletal collection using LA-MC-ICP-MS.

Sample	Bone: Pre-treated	
	Line 1	Line 2
Gu 1	0.71001 ± 0.00030	0.70940 ± 0.00033
Gu 2	0.70912 ± 0.00033	0.70927 ± 0.00032
Gu 3	0.70977 ± 0.00040	0.71028 ± 0.00042
Gu 4(5)	0.70943 ± 0.00039	0.70918 ± 0.00038
Gu 6	0.70892 ± 0.00029	0.70917 ± 0.00033
Gu 6A	0.70958 ± 0.00034	0.70936 ± 0.00042
Infant DC	0.70942 ± 0.00036	0.70933 ± 0.00036
Gu 7	0.70927 ± 0.00039	0.70949 ± 0.00035
Gu 8	0.71060 ± 0.00057	0.71084 ± 0.00064
Gu 9	0.71049 ± 0.00051	0.71023 ± 0.00056
Gu 10	0.70860 ± 0.00130	0.70790 ± 0.00240
Gu 11	0.70977 ± 0.00046	0.70939 ± 0.00042
Gu 12	0.70884 ± 0.00037	0.70909 ± 0.00029
Gu MISC	N/A	N/A
Faunal DC	0.71039 ± 0.00047	0.70860 ± 0.00130
Faunal Ja	0.70949 ± 0.00032	0.70884 ± 0.00031

Table D.2: Raw strontium isotope data ($^{87}Sr/^{86}Sr$) from the pre-treated bones (attained from the Gurat skeletal collection) using LA-MC-ICP-MS.

Standard	Sr8786	2 Standard Error
USGS-MACS3		
USGS-MACS3-1	0.707571	0.000049
USGS-MACS3-2	0.707582	0.00006
USGS-MACS3-3	0.707576	0.000054
USGS-MACS3-4	0.707532	0.000058
USGS-MACS3-6	0.707602	0.000046
USGS-MACS3-7	0.707581	0.000057
USGS-MACS3-8	0.707608	0.000054
USGS-MACS3-9	0.707639	0.000054
USGS-MACS3-10	0.707641	0.000055
USGS-MACS3-11	0.707623	0.000059
USGS-MACS3-12	0.707611	0.000052
USGS-MACS3-13	0.707626	0.000055
USGS-MACS3-14	0.707624	0.000053
USGS-MACS3-15	0.707631	0.000048
USGS-MACS3-16	0.70761	0.000052
USGS-MACS3-17	0.707593	0.000048
USGS-MACS3-18	0.707603	0.000048
USGS-MACS3-19	0.7076	0.000048
USGS-MACS3-20	0.707604	0.000049
USGS-MACS3-5	0.707633	0.000047
USGS-MACS3-21	0.707621	0.000058
USGS-MACS3-22	0.70756	0.00012

USGS-MACS3-23	0.707639	0.000056
USGS-MACS3-24	0.707628	0.00005
USGS-MACS3-25	0.707637	0.000053
USGS-MACS3-26	0.707635	0.000057
USGS-MACS3-27	0.707577	0.000057
DUAP		
DUAP-1	0.70784	0.00015
DUAP-2	0.70776	0.00018
DUAP-3	0.70791	0.00016
DUAP-4	0.70793	0.00016
DUAP-6	0.70817	0.00021
DUAP-7	0.70833	0.00023
DUAP-8	0.70792	0.00018
DUAP-9	0.70827	0.00021
DUAP-10	0.70855	0.00021
DUAP-11	0.70842	0.00014
DUAP-12	0.7084	0.00017
DUAP-13	0.7083	0.00016
DUAP-14	0.70836	0.00022
DUAP-15	0.70778	0.00061
DUAP-16	0.70817	0.00014
DUAP-17	0.70804	0.00014
DUAP-18	0.70825	0.00016
DUAP-19	0.70841	0.00014
DUAP-20	0.7083	0.00019
DUAP-5	0.70805	0.00018
DUAP-21	0.7084	0.00018
DUAP-22	0.70829	0.00019
DUAP-23	0.70844	0.00015
DUAP-24	0.70833	0.0002
DUAP-25	0.7083	0.00019
DUAP-26	0.70834	0.00021
DUAP-27	0.70816	0.00019
NIST616		
NIST616-1	0.7109	0.0019
NIST616-2	0.7082	0.0044
NIST616-3	0.711	0.0022
NIST616-4	0.7121	0.0022
NIST616-6	0.7074	0.0022
NIST616-7	0.7084	0.0023
NIST616-8	0.7061	0.0025

NIST616-9	0.7112	0.0021
NIST616-10	0.709	0.0028
NIST616-11	0.7098	0.002
NIST616-12	0.7109	0.0023
NIST616-13	0.7112	0.0021
NIST616-14	0.709	0.0022
NIST616-15	0.7084	0.0021
NIST616-16	0.7091	0.0022
NIST616-17	0.7118	0.0021
NIST616-18	0.7091	0.0022
NIST616-19	0.7079	0.0021
NIST616-20	0.7106	0.0024
NIST616-5	0.7121	0.0022
NIST616-21	0.708	0.0021
NIST616-22	0.7107	0.0023
NIST616-23	0.707	0.0023
NIST616-24	0.7065	0.0023
NIST616-25	0.7105	0.003
NIST616-26	0.71	0.0025
NIST616-27	0.7076	0.0026
SHARK		
SHARK-1	0.709135	0.000056
SHARK-2	0.709192	0.000059
SHARK-3	0.70915	0.000057
SHARK-4	0.709143	0.000059
SHARK-6	0.709232	0.000065
SHARK-7	0.709241	0.000065
SHARK-8	0.709183	0.000065
SHARK-9	0.709267	0.000065
SHARK-10	0.709293	0.000062
SHARK-11	0.709285	0.000053
SHARK-12	0.709209	0.000073
SHARK-13	0.709275	0.00008
SHARK-14	0.709217	0.00008
SHARK-15	0.709313	0.000073
SHARK-16	0.70918	0.000075
SHARK-17	0.709166	0.000067
SHARK-18	0.709153	0.000064
SHARK-19	0.709183	0.000061
SHARK-20	0.709174	0.000067
SHARK-5	0.7092	0.000074

SHARK-21	0.709223	0.000061
SHARK-22	0.709276	0.000058
SHARK-23	0.709241	0.000064
SHARK-24	0.709194	0.000074
SHARK-25	0.70918	0.00021
SHARK-26	0.709339	0.000063
SHARK-27	0.709291	0.000059

Table D.3: Strontium isotope values received from standards employed during LA-MC-ICP-MS

Comments	Rb87 as PPM	CaAr84 as PPM	Total Sr Beam	Sr8786 Uncorr	Sr8786 Corr	Rb87 Sr86ratio	Sr8486 Uncorr	Sr8486 Corr	StdCorr_Sr 87_86
PGU10-2	1200	26700	0.43340	0.71023	0.70800	0.00210	0.06926	0.05096	0.70790
PFAUNALDC-2	2100	22570	0.50680	0.71014	0.70870	0.00150	0.06573	0.05090	0.70860
PGU10-1	3400	25200	0.47190	0.71107	0.70860	0.00250	0.06777	0.05076	0.70860
PFAUNALJA-2	1700	30070	0.54710	0.71019	0.70890	0.00121	0.06350	0.04444	0.70884
PGU12-1	2230	20090	0.55310	0.71047	0.70894	0.00158	0.06333	0.05069	0.70884
BGU4-1	9810	27500	0.47030	0.71598	0.70896	0.00700	0.06472	0.04694	0.70889
BGU2-1	1680	29400	0.51850	0.71016	0.70897	0.00120	0.06514	0.04608	0.70890
PGU6-1	2380	21240	0.65690	0.71065	0.70898	0.00169	0.06476	0.05102	0.70892
BGU7-1	153000	33800	0.39600	0.97700	0.70903	0.26700	0.06550	0.04430	0.70894
BGU10-1	3580	25300	0.40520	0.71171	0.70907	0.00255	0.06668	0.04969	0.70900
BGU12-1	2290	22550	0.52500	0.71082	0.70914	0.00163	0.06393	0.04962	0.70907
PGU12-2	3460	18540	0.61550	0.71165	0.70920	0.00247	0.06306	0.05144	0.70909
BGU-INFANTDC-2	15900	31000	0.38210	0.72080	0.70918	0.01170	0.06736	0.04661	0.70911
PGU2-1	3580	30480	0.54900	0.71175	0.70922	0.00255	0.06508	0.04529	0.70912
BGU6A-2	1920	31430	0.53630	0.71063	0.70923	0.00137	0.06514	0.04484	0.70916
PGU6-2	2820	26610	0.61600	0.71137	0.70922	0.00201	0.06502	0.04786	0.70917
PGU4-2	2740	32890	0.51840	0.71107	0.70923	0.00195	0.06624	0.04447	0.70918
BGU12-2	18700	17610	0.73500	0.72320	0.70928	0.01410	0.06299	0.05180	0.70921
BGU2-2	1320	27830	0.61480	0.71020	0.70932	0.00094	0.06507	0.04689	0.70923
BGU4-2	10400	28300	0.44380	0.71650	0.70931	0.00750	0.06512	0.04660	0.70924
BGU-INFANTDC-1	5900	32760	0.49060	0.71340	0.70933	0.00430	0.06738	0.04540	0.70926
BGU7-2	1720	26280	0.48100	0.71057	0.70934	0.00123	0.06524	0.04810	0.70926
PGU2-2	3010	30700	0.58030	0.71151	0.70937	0.00214	0.06450	0.04477	0.70927
PGU7-1	2610	35300	0.50680	0.71111	0.70930	0.00186	0.06690	0.04336	0.70927
BGU3-2	2230	26200	0.43880	0.71099	0.70941	0.00157	0.06571	0.04846	0.70933
PGUINFANTDC-2	29400	26290	0.52270	0.73150	0.70940	0.02210	0.06946	0.05117	0.70933
PGU6A-2	3990	32300	0.46720	0.71226	0.70941	0.00284	0.06574	0.04452	0.70936
BGU6A-1	2250	34630	0.55280	0.71099	0.70943	0.00160	0.06485	0.04244	0.70937
BGU1-1	1310	27570	0.56740	0.71039	0.70945	0.00093	0.06469	0.04698	0.70938
FAUNALDC-2	770	23950	0.56310	0.70998	0.70943	0.00054	0.06890	0.05234	0.70938
PGU11-2	2160	29700	0.42970	0.71105	0.70949	0.00154	0.06688	0.04718	0.70939
PGU1-2	3060	30460	0.61300	0.71158	0.70944	0.00218	0.06337	0.04407	0.70940

PGUINFANTDC-1	1030	27690	0.46130	0.71024	0.70949	0.00073	0.07068	0.05113	0.70942
PGU4-1	6660	32900	0.46010	0.71448	0.70948	0.00478	0.06575	0.04409	0.70943
BGU10-2	950	24510	0.49150	0.71015	0.70950	0.00067	0.06691	0.05055	0.70944
BGU3-1	2330	27900	0.37140	0.71113	0.70952	0.00166	0.06697	0.04834	0.70944
PFAUNALJA-1	1210	30410	0.52430	0.71043	0.70955	0.00086	0.06591	0.04590	0.70949
PGU7-2	2760	29420	0.52980	0.71149	0.70953	0.00196	0.06741	0.04764	0.70949
BGU6-1	2010	28680	0.55060	0.71099	0.70959	0.00143	0.06615	0.04717	0.70952
FAUNALDC-1	930	24770	0.56780	0.71026	0.70958	0.00066	0.06863	0.05175	0.70952
PGU6A-1	2880	32680	0.51130	0.71157	0.70964	0.00205	0.06696	0.04504	0.70958
BGU11-1	1570	29100	0.36810	0.71077	0.70967	0.00111	0.06791	0.04824	0.70960
BGU6-2	1330	23230	0.61610	0.71059	0.70967	0.00094	0.06506	0.04998	0.70961
FAUNALJA-1	1730	29840	0.51120	0.71089	0.70969	0.00123	0.06469	0.04543	0.70963
FAUNALJA-2	1240	29230	0.64400	0.71059	0.70972	0.00088	0.06344	0.04498	0.70966
BGU-MISC-1	11700	30600	0.38860	0.71930	0.70982	0.01010	0.06786	0.04710	0.70976
PGU11-1	2780	32600	0.39260	0.71187	0.70987	0.00198	0.06738	0.04543	0.70977
PGU3-1	3930	29400	0.47540	0.71265	0.70984	0.00280	0.06952	0.04913	0.70977
PGU1-1	1630	32420	0.54950	0.71120	0.71006	0.00116	0.06746	0.04561	0.71001
BGU1-2	1080	18370	0.55020	0.71097	0.71020	0.00076	0.06370	0.05203	0.71013
BGU11-2	1380	27500	0.50440	0.71147	0.71029	0.00102	0.06682	0.04847	0.71022
PGU9-2	2500	32500	0.33510	0.71209	0.71029	0.00178	0.06905	0.04670	0.71023
BGU8-1	940	32500	0.46300	0.71094	0.71032	0.00067	0.06748	0.04572	0.71027
PGU3-2	1790	30800	0.41910	0.71156	0.71035	0.00127	0.06998	0.04838	0.71028
PFAUNALDC-1	1140	33200	0.36870	0.71115	0.71043	0.00081	0.07057	0.04720	0.71039
PGU9-1	1630	31200	0.35070	0.71172	0.71059	0.00116	0.06800	0.04700	0.71049
BGU9-2	1170	25400	0.39020	0.71143	0.71058	0.00083	0.06862	0.05140	0.71051
PGU8-1	1620	37100	0.30570	0.71189	0.71070	0.00115	0.07214	0.04550	0.71060
BGU9-1	1140	33900	0.33370	0.71151	0.71073	0.00081	0.06897	0.04570	0.71066
BGU-MISC-2	2040	34300	0.36460	0.71239	0.71083	0.00145	0.06748	0.04450	0.71076
BGU8-2	970	42600	0.36860	0.71152	0.71084	0.00069	0.07325	0.04207	0.71079
PGU8-2	1760	42800	0.29340	0.71217	0.71094	0.00128	0.07372	0.04230	0.71084
GU9-2	13800	48700	0.26510	0.72220	0.71140	0.01050	0.06996	0.03640	0.71140
GU2-2	11030	40000	0.36260	0.72012	0.71230	0.00792	0.06698	0.04020	0.71227
GU1-2	11520	49200	0.27570	0.72122	0.71294	0.00831	0.07150	0.03650	0.71291
GU2-1	14200	54600	0.19470	0.72338	0.71302	0.01027	0.08062	0.03680	0.71299
GU9-1	13200	66400	0.22480	0.72430	0.71360	0.01300	0.07459	0.02560	0.71350
GU3-1	22800	49300	0.17830	0.73000	0.71390	0.01740	0.09760	0.04980	0.71390
GU3-2	13000	50000	0.18880	0.72414	0.71487	0.00942	0.09440	0.04760	0.71485
GU1-1	12480	60600	0.21690	0.72413	0.71515	0.00904	0.07551	0.02970	0.71512
GU-InfantDC-1	22390	66100	0.12301	0.73150	0.71540	0.01638	0.10130	0.03510	0.71530
GU-InfantDC-2	23270	63400	0.10351	0.73270	0.71590	0.01699	0.10710	0.04080	0.71580
GU-MISC-1	19200	60200	0.10276	0.73010	0.71610	0.01410	0.10310	0.04210	0.71600

GU4-2	13520	42100	0.13941	0.72620	0.71640	0.00982	0.10070	0.05880	0.71640
GU8-1	15640	55800	0.12238	0.72830	0.71690	0.01141	0.10060	0.04500	0.71680
GU4-1	18750	57300	0.11140	0.73180	0.71820	0.01372	0.10520	0.04570	0.71820
GU8-2	19100	87200	0.10065	0.73310	0.71920	0.01402	0.11320	0.01580	0.71910
GU-MISC-2	20900	50100	0.08194	0.73480	0.71930	0.01550	0.10530	0.05400	0.71920
GU7-1	25390	66800	0.10490	0.73890	0.72030	0.01876	0.10100	0.03450	0.72020
GU7-2	23820	77100	0.10730	0.73790	0.72040	0.01758	0.08980	0.02220	0.72040
GU10-1	56300	140900	0.06620	0.76950	0.72650	0.04340	0.09850	-0.02760	0.72640
GU10-2	40600	82900	0.06453	0.75770	0.72720	0.03070	0.11750	0.02220	0.72720

Table D.4: Data received from samples during LA-MC-ICP-MS

D.3 Data Received from FTIR Spectrometry

Sample	**CI**
Gu 1	3.66
Gu 2	3.68
Gu 3	3.76
Gu 4(5)	3.52
Gu 6	3.88
Gu 6A	3.47
Infant DC	3.88
Gu 7	3.89
Gu 8	3.7
Gu 9	3.74
Gu 10	3.59
Gu 11	3.7
Gu 12	3.47
Faunal DC	3.17
Faunal Ja	3.36
Gu MISC	3.68

Table D.5: Crystallinity indices yielded from FTIR spectrometry

APPENDIX E: Diagenesis and Pre-Treatment Protocols

E.1 Pre-Treatment Protocol

Pre-treatment protocols have been effective in removing portions of skeletal material that have been affected by diagenetic alteration. For example, in their study Price et al. (1992) explore three procedures that attempt to reduce effects of diagenesis: 1) mechanical cleaning, 2) chemical cleaning through acid washing of whole bone or tooth, and 3) chemical cleaning using a reducing agent for washing a bone or tooth. Most scholars, however, follow an acid rinsing protocol (i.e. Krueger and Sullivan 1984; Sillen 1989; Price et al. 1992; Hoppe et al. 2003). The third procedure is specific to diagenetic alteration of barium.

Krueger and Sullivan (1984) were the first scholars to demonstrate that an overnight bath in that acetic acid (1N) could remove soluble carbonate contaminants (211). In order to assess the effectiveness of acid pre-treatment, Sillen (1989) analyzed the ratio between calcium and phosphate (P), which, for biological apatite, is expected to be 2 (218). Sillen (1989) concludes that pre-treatment is effective after sequentially rinsing bone samples in fresh dilute, buffered acetic acid (as the Ca/P values returned to the expected biological value of 2).

A weak acetic acid solution is widely chosen to pre-treat both tooth enamel and bone samples prior to isotopic studies. The exact acid strength and length of sample reaction time, however, are both details that vary between different pre-treatment protocols (i.e. Sillen 1989; Price et al. 1992, 2000; Budd et al. 2000; Hedges 2002; Hoppe et al. 2003; Garvie-Lok et al. 2004). Overall, many pre-treatment protocols have been developed by various scholars in order to separate biogenic strontium from diagenetic contaminants; however none have been shown to remove all diagenetic contaminants (Hoppe et al. 2003).

E.2 Application of Pre-treatment Protocol

Dilute acetic acid was chosen as a pre-treatment solution, as per methods outlined by Garvie-Lok et al. 2004. Dilute acetic acid is able to dissolve the portion of bone mineral that is likely to have been affected by diagenetic alteration (Price et al. 2000; Garvie-Lok et al. 2004).

For this research project, thirty bone samples were split into two groups: fifteen were pre-treated with the following method and fifteen were not pre-treated. Each of fifteen bone samples were soaked in 20 ml of a dilute 0.1 M acetic acid solution with a pH of ~2.8 for four hours. Tooth samples were not pre-treated as tooth enamel is relatively unaffected by diagenesis. After four hours the fifteen pre-treated samples were sonicated for 15 minutes in distilled water and left to dry for 72 hours.

After employing LA-MC-ICP-MS, $^{87}Sr/^{86}Sr$ values for both pre-treated and untreated bone samples were very similar. Furthermore, through FTIR Spectrometry it was concluded that the CI of untreated bone samples was within normal range for archaeological samples. Therefore, using the data collected from the pre-treated bone samples was decided against. Such data is presented in Appendix D, Table D.2.