IDENTIFYING NON-LOCAL INDIVIDUALS AT THE ANCIENT MAYA CENTRE OF MINANHA, BELIZE THROUGH THE USE OF STRONTIUM ISOTOPE ANALYSIS

A thesis submitted to the Committee of Graduate Studies in Partial Fulfillment of the Requirements for the Degree of Master of Arts in the Faculty of Arts and Science

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ABSTRACT

Identifying non-local individuals at the ancient Maya centre of Minanha, Belize through the use of strontium isotope analysis

Jessica Sutinen

Strontium isotope analysis has become an important tool in identifying non-local individuals at archaeological sites. For this study, tooth enamel samples were collected from 20 individuals from the ancient Maya centre of Minanha, Belize. These individuals date to periods spanning the formative occupation of the centre, as well as its fluorescence and protracted decline. The goal of this research was to investigate if non-local individuals played a role in Minanha’s formation and fluorescence. The study utilised published strontium isotope maps from Belize and the Yucatán in order to establish local $^{87}\text{Sr}/^{86}\text{Sr}$ values. The values of the Minanha enamel samples ($n=20$) fell predominantly outside of the expected strontium isotope range; this result seemed implausible and an alternative method was utilised to establish the local $^{87}\text{Sr}/^{86}\text{Sr}$ values. The outlier method identified 5/20 (25%) non-local individuals. All of the non-local individuals had $^{87}\text{Sr}/^{86}\text{Sr}$ values that coincided with published $^{87}\text{Sr}/^{86}\text{Sr}$ values reported from within 10 – 20 km of Minanha. However, some strontium isotope values also corresponded with $^{87}\text{Sr}/^{86}\text{Sr}$ values reported from regions >50 km away. The percentage of non-locals at Minanha is consistent with other Mesoamerican centres. This study emphasises the importance of collecting local baseline $^{87}\text{Sr}/^{86}\text{Sr}$ values from sites themselves, as $^{87}\text{Sr}/^{86}\text{Sr}$ values from neighbouring regions might not reflect local strontium isotope values.

Keywords: mobility, migration, biogeochemistry, bioarchaeology, movement, enamel, Vaca Plateau, socioenvironmental dynamics, mass spectrometry
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Table of Contents

ABSTRACT / ii
ACKNOWLEDGEMENTS / iii
TABLE OF CONTENTS / vi
LIST OF FIGURES / viii
LIST OF TABLES / ix

CHAPTER 1: INTRODUCTION
  1.1 Context and Research Topic / 1
  1.2 Thesis Overview / 4

CHAPTER 2: STRONTIUM ISOTOPE ANALYSIS THEORY AND BACKGROUND
  2.1 Isotopes / 6
      2.1.1 Isotopes, isotope effects, and fractionation / 6
      2.1.2 Isotope measurement / 8
      2.1.3 Strontium isotopes and properties / 10
      2.1.4 Strontium -87 and rubidium -87 / 12
  2.2 Strontium -87 in the lithosphere / 13
      2.2.1 Strontium -87 and rubidium-87 in rock and mineral deposits / 13
      2.2.2 Weathering / 14
  2.3 Strontium -87 in the biosphere / 15
      2.3.1 Strontium -87 in water sources / 15
      2.3.2 Strontium -87 in soil and plants / 18
      2.3.3 Strontium -87 in the food chain and biologically available 87Sr/86Sr / 20
  2.4 Strontium -87 in humans / 22
      2.4.1 Strontium metabolism / 22
      2.4.2 Strontium in bone and mechanisms of Ca-substitution / 23
      2.4.3 Enamel formation and strontium in enamel / 25
  2.5 Diagenesis / 27
  2.6 Summary / 29

CHAPTER 3: LITERATURE REVIEW
  3.1 Mobility in archaeology / 31
  3.2 The development of strontium isotope analysis as a bioarchaeological method / 33
  3.3 Archaeological uses of strontium isotope analysis / 35
  3.4 Application of strontium isotope analysis in Mesoamerica / 36
  3.5 Strengths and weaknesses of strontium isotope analysis / 39
  3.6 Summary / 41

CHAPTER 4: SITE AND SAMPLE
  4.1 Minanha / 43
      4.1.1 Geographical context / 43
      4.1.2 Excavations and Minanha history / 46
  4.2 Sample overview / 51
  4.3 Previous research on this sample / 54
  4.4 Summary / 55
CHAPTER 5: METHODS
5.1 Research methods / 56
5.2 Identifying non-local $^{87}$Sr/$^{86}$Sr values / 57
5.3 Laboratory methods / 58
5.4 Instrumentation / 61
   5.4.1 Trent University / 62
   5.4.2 Memorial University / 62
5.5 Sample preservation / 62
5.6 Statistical methods / 63
5.7 Summary / 63

CHAPTER 6: RESULTS
6.1 Sample integrity / 64
6.2 Analytical accuracy and precision / 64
6.3 Strontium isotope analysis results / 65
6.4 Outlier method / 69
6.5 Baseline method / 71
6.6 Spatiotemporal significance of the data / 76
6.7 Summary / 79

CHAPTER 7: DISCUSSION AND CONCLUSIONS
7.1 Sample viability and comparison to other Mesoamerican samples / 81
7.2 Factors affecting viable $^{87}$Sr/$^{86}$Sr values / 84
7.3 Non-local individuals at Minanha / 87
   7.3.1 Specimen 3 (Feature 3A-F/4) / 88
   7.3.2 Specimen 10-13v (Burial 77S-B/2) / 89
   7.3.3 Specimen 21 (Burial 53S-B/2) / 90
   7.3.4 Specimen 23ii (Burial MRS4-M3-B1) / 93
   7.3.5 Specimen 37 (Burial 42K-B/1) / 94
   7.3.6 Characteristics of the non-local individuals at Minanha / 94
7.4 Mobility during periods of drought and through time / 96
7.5 Elite mobility / 100
7.6 Local individuals / 101
7.7 Research summary / 102
7.8 Limitations / 103
7.9 Future directions / 103

REFERENCES CITED / 105
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Simplified mass spectrometer diagram</td>
<td>10</td>
</tr>
<tr>
<td>4.1</td>
<td>Map of Maya subarea</td>
<td>44</td>
</tr>
<tr>
<td>4.2</td>
<td>Map of the Vaca Plateau</td>
<td>45</td>
</tr>
<tr>
<td>4.3</td>
<td>Map of the Minanha epicentre and site core</td>
<td>49</td>
</tr>
<tr>
<td>4.4</td>
<td>Map of Minanha and Contreras Valley</td>
<td>49</td>
</tr>
<tr>
<td>5.1</td>
<td>Strontium isotope zones of the Yucatán Peninsula</td>
<td>59</td>
</tr>
<tr>
<td>6.1</td>
<td>Scatterplot of Minanha $^{87}\text{Sr}/^{86}\text{Sr}$ values</td>
<td>70</td>
</tr>
<tr>
<td>6.2</td>
<td>Trimmed scatterplot I</td>
<td>71</td>
</tr>
<tr>
<td>6.3</td>
<td>Trimmed scatterplot II</td>
<td>72</td>
</tr>
<tr>
<td>6.4</td>
<td>Trimmed scatterplot III</td>
<td>72</td>
</tr>
<tr>
<td>6.5</td>
<td>Bar graph of Minanha $^{87}\text{Sr}/^{86}\text{Sr}$ values</td>
<td>73</td>
</tr>
<tr>
<td>6.6</td>
<td>Strontium zones surrounding Minanha</td>
<td>74</td>
</tr>
<tr>
<td>6.7</td>
<td>Bar graph of suggested Minanha $^{87}\text{Sr}/^{86}\text{Sr}$ range</td>
<td>75</td>
</tr>
<tr>
<td>6.8</td>
<td>Boxplot of $^{87}\text{Sr}/^{86}\text{Sr}$ values according to burial location</td>
<td>77</td>
</tr>
<tr>
<td>6.9</td>
<td>Boxplot of $^{87}\text{Sr}/^{86}\text{Sr}$ values according to grave type</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>Boxplot of $^{87}\text{Sr}/^{86}\text{Sr}$ values pertaining to Maya time</td>
<td>79</td>
</tr>
<tr>
<td>6.10</td>
<td>periods</td>
<td></td>
</tr>
<tr>
<td>6.11</td>
<td>Boxplot of $^{87}\text{Sr}/^{86}\text{Sr}$ values pertaining to drought periods</td>
<td>79</td>
</tr>
<tr>
<td>7.1</td>
<td>Grave drawing of Specimen 21</td>
<td>92</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Chronology and site development at Minanha</td>
<td>48</td>
</tr>
<tr>
<td>4.2</td>
<td>Specimen information</td>
<td>54</td>
</tr>
<tr>
<td>5.1</td>
<td>Tooth condition and sampling information</td>
<td>60</td>
</tr>
<tr>
<td>6.1</td>
<td>Specimen $^{87}\text{Sr}/^{86}\text{Sr}$ values</td>
<td>66</td>
</tr>
<tr>
<td>6.2</td>
<td>Comparison of Water Quality Centre and Memorial University $^{87}\text{Sr}/^{86}\text{Sr}$ values</td>
<td>67</td>
</tr>
<tr>
<td>6.3</td>
<td>Duplicate and intra-tooth $^{87}\text{Sr}/^{86}\text{Sr}$ values</td>
<td>67</td>
</tr>
<tr>
<td>6.4</td>
<td>Inter-tooth $^{87}\text{Sr}/^{86}\text{Sr}$ values</td>
<td>68</td>
</tr>
<tr>
<td>6.5</td>
<td>$^{87}\text{Sr}/^{86}\text{Sr}$ ranges suggested by different trimming techniques</td>
<td>76</td>
</tr>
<tr>
<td>7.1</td>
<td>Non-local population percentages reported at other Maya centres</td>
<td>82</td>
</tr>
<tr>
<td>7.2</td>
<td>Freiwald’s (2011) Belize River Valley $^{87}\text{Sr}/^{86}\text{Sr}$ values</td>
<td>83</td>
</tr>
<tr>
<td>7.3</td>
<td>Stable carbon and nitrogen isotope values of specimens in this study from Stronge (2012)</td>
<td>85</td>
</tr>
<tr>
<td>7.4</td>
<td>Minanha non-locals identified by different trimming methods</td>
<td>87</td>
</tr>
<tr>
<td>7.5</td>
<td>Contextual information of non-local individuals</td>
<td>88</td>
</tr>
<tr>
<td>7.6</td>
<td>$^{87}\text{Sr}/^{86}\text{Sr}$ values of specimens from Burial 77S-B/2</td>
<td>90</td>
</tr>
<tr>
<td>7.7</td>
<td>$^{87}\text{Sr}/^{86}\text{Sr}$ values and contextual data for individuals with dental modification</td>
<td>91</td>
</tr>
<tr>
<td>7.8</td>
<td>Contreras Valley individuals</td>
<td>93</td>
</tr>
<tr>
<td>7.9</td>
<td>Specimen $^{87}\text{Sr}/^{86}\text{Sr}$ values and possible origins</td>
<td>95</td>
</tr>
<tr>
<td>7.10</td>
<td>Non-local variables described by Freiwald (2011)</td>
<td>96</td>
</tr>
<tr>
<td>7.11</td>
<td>Non-local individuals during drought periods at Minanha</td>
<td>98</td>
</tr>
</tbody>
</table>
7.12 Specimens dating to royal rule at Minanha 101
Chapter 1: Introduction

1.1 Context and Research Topic

Movement is an important concept in archaeology, and has been since the early 1900’s when archaeologists examined diffusion and migration as agents of cultural change (reviewed in Beaudry and Parno 2013 [see Childe 1951; Smith 1929]). It is an umbrella term, encompassing all forms of movement in the past, and thus, for example, can refer to: the movement of residential camps (Surovell 2000; Hofman et al. 2006; Diaz et al. 2012); the movement of animals (Viner et al. 2010; Arnold et al. 2013; Shaw et al. 2009); a shift in the degree of movement (Schachner et al. 2011; Bentley et al. 2003; Jones 2012); large-scale migrations (Matisoo-Smith et al. 1998); or trade (McManus et al. 2013; Roberts et al. 2013; Walsh and Mocci 2011; Gomez et al. 2011; Aubry et al. 2012). A more circumscribed, yet explanatory definition of movement is mobility.

Mobility alludes to the implications behind movement and the ramifications because of it. Cresswell (2010:29) defines it as “[t]he entanglement of movement, representation, and practice.” Mobility does not have the mutually exclusive freedom that movement suggests. For modern archaeologists, operating under the definition of mobility requires the elucidation of the underlying factors of movement.

This thesis concerns the identification of mobility in the bioarchaeological record and what it can elucidate about the socioenvironmental long-term dynamics of a medium-sized ancient Maya centre in Belize. The Social Archaeology Research Project (SARP) has excavated at the ancient Maya centre of Minanha for over 12 years and has developed a long-term, transdisciplinary approach. This technique has produced archaeological evidence spanning from the first habitation of Minanha to its near abandonment almost 1500 years later in addition to climatological information.
elucidating Minanha’s climate during the entire span of its occupation. The social, political, and environmental knowledge acquired by SARP permits an examination of mobility at Minanha: these factors represent the entanglements described by Creswell (2010:29) that limit, are inherent in, and comprise the consequences of, movement.

To examine mobility in the archaeological record at Minanha, non-local individuals were identified using a bioarchaeological approach. Bioarchaeology seeks to explain past human behaviour within a biocultural framework by examining ancient or historic human remains and interpreting behaviour from collected evidence (Martin et al. 2013:1). Bioarchaeological techniques are expedient because they are capable of identifying certain behaviours from the examination of an individual’s physical remains, and therefore represent direct lines of evidence. Bioarchaeological approaches are useful in mobility studies because conventional archaeological methods examining mobility require the use of proxies; although useful, it is often difficult to discern, for example, whether the appearance of new ceramic styles or architecture represent the movement of people or ideas. However, the comparison of both conventional archaeological and bioarchaeological evidence is a powerful tool in archaeology and it is often done to strengthen or refute conjectures and arguments.

This thesis project examined mobility at Minanha through the identification of non-local individuals by strontium isotope analysis. This method, adopted into bioarchaeology during the mid-1980’s (see Ericson 1985), measures the ratio of strontium isotopes 87 and 86 \((^{87}\text{Sr}/^{86}\text{Sr})\) in human hydroxylapatite. This ratio originates in bedrock and is often unique to distinct geographic regions. It is released into soil and water and taken up by plants and animals. In turn, humans, consuming plants and animals and water, incorporate the \(^{87}\text{Sr}/^{86}\text{Sr}\) ratio into their skeletal system. By determining the local \(^{87}\text{Sr}/^{86}\text{Sr}\) of Minanha, it was possible to identify non-locals to
the centre and to infer mobility by comparing individual $^{87}\text{Sr}/^{86}\text{Sr}$ ratios to those local to Minanha.

Mobility is of particular interest to archaeologists studying the ancient Maya. Other published strontium isotope analysis studies have reported non-local population percentages of ~10-30% (see Freiwald 2011; Price et al. 2010; Wright et al. 2005; Wright et al. 2010), suggesting that non-local individuals comprise a significant portion of the population (i.e., Wright et al. 2005). In addition, the underlying reasons for identified mobility in the Maya Yucatán are varied, and include, but are not limited to, political and diplomatic agendas (see Price et al. 2010).

SARP’s socioenvironmental approach to understanding the long-term dynamics at Minanha permits an examination of mobility in the archaeological environments of social, political, and climatic events. As such, this thesis examined mobility in the contexts of political change (i.e., the founding and dismantlement of the royal court) and climatic stress (i.e., drought). Mobility through the 1500 years of Minanha’s occupation was also examined, with particular attention given to the different periods of the Maya chronology. In addition, SARP’s long-term excavations at Minanha have provided burial contextual data for each individual included in the sample, which has allowed for an individualised approach to examining non-locals at Minanha. It is important to determine who the non-locals were as modern studies “suggest that movement does not occur equally across the population” (Freiwald 2011:362). For example, relationships between non-local individuals and burial rituals such as body orientation and grave type were explored (see Freiwald 2011).

In addition, this thesis will contribute to the accumulating knowledge on archaeological strontium isotope ratios in the Yucatán (see Freiwald 2011; Hodell 2004; Price et al. 2010; White et al. 2007; Wright 2005a; Yaegar and Freiwald 2009).
Thus, the purpose of this thesis is to examine mobility at Minanha in the context of socioenvironmental factors. Specifically, it attempts to elucidate whether or not known events (i.e., drought, the establishment of the royal court) affected mobility (i.e., increased/decreased mobility to Minanha). It also compares mobility at Minanha to that of other centres and regions in the Maya subarea. In addition, it explores mobility on the level of the individual. Grave offerings, grave type, and location are examined alongside the strontium isotope values to give further insight into the lives of the individuals in this study.

1.2 Thesis Overview

Following this chapter, Chapter 2 provides an overview of the theory behind strontium isotope analysis including an examination of isotopes and their physicochemical properties, strontium’s presence in the environment and incorporation into the human skeletal system, the measurement of strontium isotopes by MC-ICP-MS, and finally how archaeologists can use strontium isotope analysis to identify non-local individuals. Chapter 3 is a review of the relevant literature and provides an overview of the development of strontium isotope analysis, its incorporation into archaeology as a bioarchaeological method, and how it has been used to identify non-local individuals in the Maya subarea. Chapter 4 provides information relating to Minanha, including site and excavation history, and details about the sample and its condition. Chapter 5 presents the techniques utilised to prepare the sample for mass spectrometry and the process followed for measurement by MC-ICP-MS. In addition, it discusses diagenesis and outlines the method that we attempted to use to assess the integrity of the samples. Lastly, it presents the statistical tests used to examine the significance of the data. Chapter 6 presents the results of mass spectrometry as well as the significance of the data. Chapter 7 is a
discussion of the significance of the data in the context of Maya archaeology and with reference to SARP’s research initiatives. In addition, it summarises the thesis research and discusses limitations as well as future directions.
Chapter 2: Strontium Isotope Analysis Theory and Background

This chapter provides the theoretical background for the use of strontium isotope analysis in bioarchaeology. More specifically, it offers a description of stable and radioisotopes and their physicochemical behaviour, their formation and abundance, and how they are measured. Subsequently, the focus is narrowed to strontium, specifically strontium-87 ($^{87}$Sr), and its release from the Earth’s crust, movement through the physical environment, and finally incorporation into biological tissues. Particular attention is paid to how $^{87}$Sr is incorporated into human bone and tooth tissue and how, by measuring the amount of $^{87}$Sr in these tissues, it is possible to determine the geographic origin of the strontium. Diagenesis and its effect on both dental and bone tissue is discussed and protocols for mitigating its effects are described.

2.1 Isotopes

2.1.1 Isotopes, isotope effects, and fractionation

Isotopes are atoms of the same element that have different numbers of neutrons. Unlike protons and electrons, neutrons do not carry a charge, but they do have a significant subatomic mass which affects the total mass of the atom, giving each isotope of an element a distinct mass. Although isotopes of an element exhibit similar chemical behaviour, the difference in mass between isotopes results in differential physical behaviour; however, because physical and chemical properties are intrinsically related, chemical behaviour may be influenced in terms of reaction time, equilibrium rates, or molecular isotopic composition (Attendorn and Bowen 1997:10). Changes in chemical behaviour due to isotopic influence result from the isotope effect, a phenomenon which is comprised of two principal classes: kinetic isotope effects (KIE) and equilibrium isotope effects.
During a chemical reaction, isotopologues (i.e., molecules that have identical chemical formulas but that vary in their isotope content) react at different rates due to KIEs that arise principally from the mass differences of the isotopes and their effect on the vibrational energies of the chemical bonds. Equilibrium isotope effects, also operating off of the mass differences of isotopes and their effects on vibrational energies, affect the equilibrium constant (the ratio of concentrations when equilibrium occurs) of a reaction. When an isotope effect is present in a reaction, it results in isotopic fractionation (i.e., a difference in isotope ratios during a physical or chemical process).

In general, heavier atoms have lower vibrational energies and shorter, stronger chemical bonds than lighter atoms. Therefore, it requires more bond energy (the energy required to sever a chemical bond) to break the bonds of heavier atoms than those of lighter atoms. Thus, in most cases, the amount of energy that a system can produce determines the extent of fractionation within that system. When fractionation does occur, reactants become enriched in the heavier isotope due to the greater bond energy required to sever the bonds of the heavier isotopes. Products, conversely, become enriched in the lighter isotope because less bond energy is required to break their chemical bonds.

Isotopes are categorised principally in relation to their atomic stability: stable isotopes do not undergo any type of decay process that would transform them into a different isotope, or they have half-lives that are too long to measure observable decay (Hoefs 2009). Radioactive isotopes are subject to radioactive decay, which is the spontaneous emission of energy (radiation) in the form of alpha, beta, or gamma rays from the nucleus of the atom (Hoefs 2009). The discharge of any of these subatomic particles transmutates the isotope into an isotope of a different element, or transforms
it into a different isotope of the same element. Isotopes produced by decay processes are radiogenic isotopes, and they themselves may be either radioactive or stable. Of all known isotopes, there are approximately 340 that occur naturally (i.e., not man-made) on Earth, the majority (~255) being stable isotopes (Hoefs 2009:3). These naturally-occurring stable isotopes are primordial, or produced from nucleosynthesis (the creation of atomic nuclei from protons and neutrons) processes in universal events (nucleosynthesis in supernovae or stars) predating the formation of the solar system. As previously mentioned, they are assumed to be stable because their half-lives are longer than $4.54 \times 10^9$ years (the age of the Earth), and therefore any observable decay has not occurred. The remaining 85 are radioactive, with varying half-lives, and undergo decay into other radiogenic stable or radioactive isotopes. Although 340 natural isotopes are recognised, artificial nuclear fusion processes have created over 1650 man-made isotopes (e.g., $^{90}$Sr), all of which are radioactive, with the majority having very brief half-lives (McSween and Huss 2010:30).

Naturally occurring isotopes exist in different relative abundances on Earth due to their rate of decay, their parent isotope’s rate of decay, or the initial, unchanging (some stable isotopes) amount produced during nucleosynthesis. For example, oxygen (O) has three naturally occurring isotopes with abundances of: $^{16}$O (99.762%), $^{17}$O (0.0380%), and $^{18}$O (0.020%). These abundances will remain the same because all three isotopes are stable and non-radiogenic.

2.1.2 Isotope measurement

The isotopic composition of a sample is determined by measuring the ratio of two stable isotopes relative to an accepted standard using a mass spectrometer (Sharp 2007). The standard is selected and controlled by the International Atomic Energy Association (IAEA) (the governing international organisation for nuclear research) for
the purpose of validity and reproducibility amongst all experimental designs. Isotope concentrations are minute and difficult to measure absolutely, so they are measured relative to a standard to eliminate any instrument error or bias, thus allowing for reproducibility and validity between different labs (McKinney et al. 1950). This applies to any fractionation that may occur during mass spectrometry as well. The relative differences in isotope ratios (sample vs. standard) are expressed by the delta ($\delta$) value, defined by the formula below (McKinney et al. 1950):

$$\delta = \left( \frac{R_x - R_{std}}{R_{std}} \right) \times 1000$$

Where $R$ is the abundance of the heavy isotope to the light isotope, $x$ represents the sample, and $std$ is the standard. This component of the equation is multiplied by 1000 to inflate the tiny differences in isotope abundances. The resultant $\delta$ value is reported as per mil ($‰$).

The relative abundance of any isotope within a substance is measured using mass spectrometry (see Figure 2.1). There are a variety of mass spectrometers with numerous configurations, however the measurement process is fundamentally similar (reviewed in Sharp 2007:16-19). A sample is first injected into the sample inlet and then vaporised (undergoes a phase change from a liquid or solid to a gas) before being combined with an inert or unreactive carrier gas. The gaseous mixture then travels into an ionisation chamber where the atoms are bombarded by electrons. These collisions remove electrons from the atoms in the vaporised sample, creating cations (positively-charged ions). The cations exit the ionisation chamber and are accelerated through a series of charged parallel plates that focus them into a beam and give each ion the same kinetic energy. This beam then passes through a curved component of the instrument where an externally-applied magnetic field interacts with that generated
by the accelerated ion beam. The trajectory of the ions is bent (deflected) in varying degrees by the magnetic field depending on their mass/charge (m/z) ratio. Ions with the greatest masses will be the least deflected, while those with relatively light masses will be more strongly deflected. Detection occurs as the deflected ions collide with a metal detector plate. Electrons jump from the plate to the ion, neutralising its charge. The movement of the electrons on the metal plate is measured as an electric current, and is output for analysis as ion spectra.

The precision that a mass spectrometer is able to achieve is dependent on its type and configuration. For example thermal ionisation mass spectrometry (TIMS) is precise to the sixth decimal place (Copeland et al. 2010), whereas inductively-coupled multi-collector mass spectrometry (ICP-MC-MS, utilised in this research project) is precise to the fourth decimal place (Copeland et al. 2010).

2.1.3 Strontium isotopes and properties

Strontium (Sr), in pure elemental form, is a divalent, solid, silver-coloured metal in the alkaline earth metal family. Like other members of that group, its electron configuration (Sr²⁺) makes it highly reactive, and it is therefore not found
naturally in pure elemental state, but rather as part of ionic compounds, the majority of which are minerals. Its abundance within the Earth’s crust (0.0384%) makes it the 15th most abundant element (Ober 2006:925).

There are 35 known isotopes of strontium, four of which are stable and exist in the relative abundances of: $^{84}\text{Sr}$ (0.56%); $^{86}\text{Sr}$ (9.86%); $^{87}\text{Sr}$ (7.0%); and $^{88}\text{Sr}$ (82.58%) (Pollard et al. 2007:174). The static quantities (with the exception of $^{87}\text{Sr}$, which is both primordial and radiogenic) of stable strontium isotopes on Earth were determined by stellar nucleosynthesis processes which created the isotopes before and during Earth’s formation (Burbridge et al. 1957). $^{87}\text{Sr}$ is also radiogenic, and while the other three stable isotopes are invariant in their abundance relative to one another, the amount of $^{87}\text{Sr}$ will increase over time and varies widely throughout different geologic formations (Faure and Powell 1972). Stable strontium isotopes originate in bedrock as the sulphate mineral celestine (SrSO$_4$) and in the carbonate mineral strontianite (SrCO$_3$), but they occur predominantly as substitutes for calcium (Ca) and barium (Ba) in Ca- and Ba-bearing minerals because their ionic radii are similar in size (Sr=1.13 Å; Ca=99 Å; Ba= 135 Å, Oxtoby et al. 2008) as divalent cations ($\text{Sr}^{2+}$, $\text{Ca}^{2+}$, $\text{Ba}^{2+}$) (Capo et al. 1998). Weathering processes release strontium into more active systems such as the water table or soils (see section 1.2.2) (Graustein 1989), where its heavier atomic mass (87.62 amu) prevents it from fractionating as readily as lighter elements in geological or biological processes (Capo et al. 1998). Once released from rock through weathering processes, it is incorporated into soil, plants, and animals, making it a common trace element whose abundance within living tissue is dose-dependent (Pan et al. 2009).

The remaining 31 radioactive isotopes are produced synthetically by nuclear fission in reactors or as by-products of nuclear weapon fallout (Vajda and Kim 2010).
The majority of these isotopes have very short half-lives, in the order of minutes to milliseconds, although $^{90}$Sr and $^{89}$Sr have half-lives of 28.9 years (Martin et al. 1994) and 50.57 days (Vajda and Kim 2010) respectively. $^{89}$Sr’s radioactivity has been harnessed and is used in the palliative treatment of bone cancers (Silberstein and Williams 1985; Kloiber et al. 1987). However, $^{90}$Sr is particularly hazardous because it contaminates human water and food sources and, after ingestion, the majority is incorporated into bone where high-energy radiation from its daughter isotope, yttrium-90, causes carcinogenic mutations (Finkel 1958; Owen and Vaughan 1960).

2.1.4 Strontium-87 and rubidium-87

Of particular importance to this thesis is the stable isotope strontium-87. Initially, its abundance on Earth was determined primordially during stellar nucleosynthesis processes as the Earth was formed (Attendorn and Bowen 1997); however it is also radiogenic, and increases in relative abundance to the other three stable strontium isotopes due to the decay of its parent isotope, rubidium-87.

$^{87}$Rb is one of two naturally-occurring isotopes of rubidium and exists in the relative abundance (to $^{85}$Rb) of 27.83% (Catanzaro et al. 1969). Rubidium, like strontium, is very abundant within the Earth’s crust and, like other members of the alkali metal group, is highly reactive. Unlike strontium, it does not form ionic compounds, but routinely substitutes for potassium (K) (Attendorn and Bowen 1997) in K-bearing minerals due to its similarly-sized ionic radius (Rb =1.52 Å; K=1.38 Å) (Capo et al. 1998).

Of the two naturally-occurring rubidium isotopes, only $^{87}$Rb is radioactive, although its half-life (4.92×10^{10} years) exceeds the age of the universe and consequently undergoes decay into $^{87}$Sr at a very slow rate. The decay of $^{87}$Rb into $^{87}$Sr also partially determines the abundance of $^{87}$Sr in certain rocks (Faure and Powell
1972), which is measured as a ratio \( \frac{^{87}\text{Sr}}{^{86}\text{Sr}} \) due to the difficulty in measuring absolute isotope abundances \( ^{86}\text{Sr} \) is stable and non-radiogenic [its abundance will not increase or decrease due to radioactive decay] and is therefore used to measure the relative abundance of \( ^{87}\text{Sr} \) (McKinney et al. 1950). However, the abundance of \( ^{87}\text{Sr} \) in any rock is always partially determined by the amount of primordial \( ^{87}\text{Sr} \) deposited during Earth’s formation (Attendorn and Bowen 1997), the accepted value being (determined as a \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratio) 0.698990 ± 0.000047 (Misra 2000). Nevertheless, over time, geochemical processes have altered the \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratio of the Earth, resulting in a diverse mosaic of \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratios throughout different geologic formations (Attendorn and Bowen 1997).

### 2.2 Strontium-87 in the lithosphere

#### 2.2.1 Strontium-87 and rubidium-87 in rock and mineral deposits

All strontium isotopes originate in rock, either deposited primordially during Earth’s formation or, for \( ^{87}\text{Sr} \), after the radioactive decay of \( ^{87}\text{Rb} \). The \( ^{87}\text{Sr}/^{86}\text{Sr} \) of any rock is dependent primarily on three factors: 1) the \( \text{Rb/Sr} \) ratio; 2) the amount of time that has elapsed since rock formation; and 3) the \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratio at the time of rock crystallisation (Faure and Powell 1972).

Both strontium and rubidium are lithophilic (rock-loving) elements (Frisch et al. 2011), however the manner in which they are incorporated into rock and the types of rock that they prefer are different. Strontium is capable of forming the minerals strontianite \((\text{SrCO}_3)\) and celestite \((\text{SrSO}_4)\), although it occurs most frequently within rock by substitution for calcium, barium, or potassium in different minerals (Misra 2000). This substitution occurs because strontium’s ionic radius as a divalent cation is similar in size to those of barium and calcium (Oxtoby et al. 2008). Strontium can also substitute for potassium in minerals where silicon \((\text{Si}^{4+})\) has been replaced by
aluminium (Al$^{3+}$) (Capo et al. 1998). Conversely, rubidium cannot form its own minerals, but its similar ionic radial size to potassium (Rb =1.52 Å; K=1.38 Å) (Capo et al. 1998) allows it to substitute for potassium in K-bearing minerals (Attendorn and Bowen 1997). Due to potassium’s preference for silicate minerals, rubidium is more commonly found in silicate rock whereas strontium is more abundant in carbonates and sulphates (Faure and Powell 1972).

During rock formation, the amount of rubidium incorporated into the minerals of the rock directly affects the $\frac{^{87}Sr}{^{86}Sr}$ ratio because $^{87}$Rb decays into $^{87}$Sr (Faure and Powell 1972; Faure 1986). In a closed geologic system, the only new source of $^{87}$Sr is $^{87}$Rb (Capo et al. 1998); therefore, rocks with greater Rb/Sr ratios will have higher $\frac{^{87}Sr}{^{86}Sr}$ ratios (Capo et al. 1998). Also important is the age of the rock; in rocks with similar initial Rb/Sr ratios, the $^{87}$Rb in older rocks will have had more time to decay into $^{87}$Sr than the $^{87}$Rb of younger rocks (Faure and Powell 1972). Lastly, during rock formation, the amount of $^{87}$Sr incorporated into the minerals of the rock supplies the rock with an initial $\frac{^{87}Sr}{^{86}Sr}$ ratio (Faure 1986). However, weathering and geologic processes (Faure 1986), fractionation (Capo et al. 1998), and the decay of $^{87}$Rb can alter a rock’s original $\frac{^{87}Sr}{^{86}Sr}$ ratio (Faure and Powell 1972).

### 2.2.2 Weathering

$^{87}$Sr transitions from the lithosphere to the biosphere through the breakdown of rock and mineral deposits caused by chemical and physical weathering processes (Faure and Powell 1972). Although both mechanisms are essential components of soil formation (Meenaskhi 2005), and therefore the incorporation of $^{87}$Sr into soil, they also release $^{87}$Sr into water and different geologic substrates (Wicander et al. 2006).

Physical weathering is the decomposition of a rock into smaller components, although these retain their original chemical composition (Chorley et al. 1984), and it
may be caused by a number of varying mechanical processes including frost shattering, pressure release, thermal stress, and haloclasty (formation of salt crystals) (Wicander et al. 2006). Although physical weathering does not extricate $^{87}$Sr from rock, the breakdown of rock into smaller components creates a greater surface area for chemical activity (Meenakshi 2005).

Chemical weathering changes the chemical composition of minerals into more stable minerals or secondary mineral materials that are in equilibrium with their surrounding chemical and physical environments (Shand et al. 2007). Water, acids, and oxygen are the principal agents of chemical weathering although atmospheric gases and plant life are also sources of chemical change (Wicander et al. 2006).

Minerals weather at different rates due to their varying chemical compositions (Graustein 1989). Specifically, minerals that crystallise during formation in a high temperature melt (e.g., Ca-plagioclase) are less resistant to weathering than those that form in lower temperatures (e.g., quartz) (Anderson and Anderson 2010). If a rock undergoing weathering processes is heterogeneous in its mineral composition, the surrounding soil or water that weathered $^{87}$Sr is released into will not have an identical $^{87}$Sr/$^{86}$Sr ratio to the parent bulk rock because the minerals that comprise it weather at different rates (Graustein 1989). In addition, some weathering processes fractionate the strontium content of minerals, resulting in a preferential loss of the lighter isotope (de Souza et al. 2007).

### 2.3 Strontium-87 in the biosphere

#### 2.3.1 Strontium-87 in water sources

The $^{87}$Sr content in water is not derived from a single source or parent rock, but is rather a mixing of $^{87}$Sr concentrations originating from weathered mineral deposits and atmospheric sources (Shand et al. 2007). Without atmospheric input, the
$^{87}\text{Sr}$ concentration of any collection of water is determined by initial variations of $^{87}\text{Sr} / ^{86}\text{Sr}$ in its source, different geologic formations and mineralogy along its flow path and their varying weathering rates, and residence times throughout the duration of its movement (Aberg and Hamilton 1989; Shand et al. 2007).

Generally, the $^{87}\text{Sr} / ^{86}\text{Sr}$ content of groundwater is similar to the strontium isotopic composition of local bedrock (Perry et al. 2009). However, it may differ slightly from the bulk rock strontium isotopic composition due to differing weathering rates (Aberg and Hamilton 1989; Graustein 1989; Shand et al. 2007) or because fault lines, flow channels, and other geologic structural features may introduce additional $^{87}\text{Sr}$ by providing pathways for foreign-sourced water (Perry et al. 2009). In addition, slow-moving groundwater will acquire more of the local bedrock strontium isotopic composition, but fast-moving will retain the $^{87}\text{Sr}$ content of its origin (Perry et al. 2002).

Aquifers, like groundwater, can acquire the strontium isotopic composition of surrounding bedrock and can be subject to a mixing of local $^{87}\text{Sr}$ content with foreign material introduced from alternative water sources (Perry et al. 2009). However, if they are a closed-system aquifer, or surrounded by particularly dense bedrock, the incorporation of additional $^{87}\text{Sr}$, if any, would be minimal (Perry et al. 2009).

The $^{87}\text{Sr} / ^{86}\text{Sr}$ compositions of streams are complex and are related to flow and weathering rates, incorporation of other water sources, and precipitation (Faure 1986). At high elevations (where there are increased weathering rates, less precipitation, and less influence from other water systems) stream water strontium isotopic concentrations were closely correlated with bedrock concentrations during high flow periods, but not during periods of low flow (Aubert et al. 2002). Conversely, a study in Scotland found that stream water $^{87}\text{Sr} / ^{86}\text{Sr}$ ratios did not fluctuate with changing
flow rates (Bain et al. 1998). These two studies highlight the inconsistencies of predicting strontium isotopic compositions in running water systems. At lower elevations where streams are more subject to influence from other systems, variability in strontium isotopic compositions may reflect the incorporation of strontium from foreign sources (Eastin and Faure 1978). Rivers, as an amalgamation of many different water sources, are inconsistent in their $^{87}$Sr content and are characterised by strontium isotopic compositions that are a combination of different sources including precipitation, tributaries, and upstream sediments and rocks (Wadleigh et al. 1985).

Atmospheric sources, including precipitation and aerosols, can be large contributors to water system $^{87}$Sr content. Probst and colleagues (1992, 2000) found that approximately 50% of dissolved strontium in stream water was derived from precipitation and atmospheric sources at a catchment site in France. Precipitation acquires its $^{87}$Sr content from the water sources that it evaporates from as well as airborne dust and pollutants, making it variable in its strontium isotopic composition (Faure 1986). Sources of strontium isotopes in airborne particles include physically-weathered minerals and fly ash from coal combustion (Graustein 1989); these particles can be transported over large distances through the atmosphere (Dymond et al. 1974). Precipitation evaporating over the oceans has a uniform strontium isotopic concentration, but the amount of oceanic strontium decreases rapidly as precipitation moves inland, becoming only a minor influence on precipitation $^{87}$Sr content at more than one hundred kilometres inland (Graustein 1989).

All water eventually reaches the ocean, and it transports weathered $^{87}$Sr along with it (Graustein 1989). As the confluence of the Earth’s largest water systems, the ocean is the largest reservoir of strontium on Earth (Graustein 1989) and has a uniform $^{87}$Sr/$^{86}$Sr composition due to strontium’s long residence time in the ocean (~2
myr) (Ravizza and Zachos 2006) and the comparatively brief mixing time of the ocean (~1000 yr) (Graustein 1989), which disperses chemical elements evenly throughout the ocean if they have a longer residence time than the ocean’s mixing period.

Weathering of three end-members is fundamental in the determination of oceanic $^{87}\text{Sr}/^{86}\text{Sr}$ compositions: that of the continental crust, young oceanic basalts, and marine carbonates (Brazz 1976; Ravizza and Zachos 2006).

The flux of $^{87}\text{Sr}$ entering the ocean is mitigated by its removal and incorporation into marine carbonates and the release of $^{86}\text{Sr}$ from oceanic basalts (Miller 1990); these balancing processes allow for the $^{87}\text{Sr}/^{86}\text{Sr}$ concentration to remain constant (Miller 1990). However, an intensification of the erosion of the continental crust during large-scale geologic processes such as continental uplift, glaciation, etc. will increase the amount of weathered $^{87}\text{Sr}$ deposited into the ocean (Lane, 2002). This will change the strontium isotopic composition of the ocean (Faure 1986); this occurs approximately every 60 million years (Melott et al. 2012).

2.3.2 Strontium -87 in soil and plants

The $^{87}\text{Sr}/^{86}\text{Sr}$ composition of any soil is a combination of atmospheric, mineral, and water inputs (Shand et al. 2007) and is, in part, a function of depth: typically, deeper soil is influenced more strongly by bedrock $^{87}\text{Sr}/^{86}\text{Sr}$ concentrations relative to shallower soil, which is influenced predominantly by atmospheric sources (Probst et al. 2000; Poszwa et al. 2002). However, factors such as ground water depth and proximity to water sources such as streams and rivers can upset this stratigraphic function of $^{87}\text{Sr}/^{86}\text{Sr}$ compositions in soil (Sillen et al. 1998). Strontium fluxes are unique to the environment that they are a component of and therefore can produce varying $^{87}\text{Sr}/^{86}\text{Sr}$ soil concentrations within a single geographic locale, or be relatively
uniform throughout a large area (Dasch 1969; Hurst and Davis 1981; Poszwa et al. 2002).

Plant life requires calcium, an essential nutrient, to fulfill structural and intracellular roles that are critical to the maintenance and health of all plant species (Marschner 1995). Strontium cations (Sr$^{2+}$), like calcium cations (Ca$^{2+}$), within the soil matrix are attracted to the negatively-charged roots of plants (Capo et al. 1998), and strontium’s similar radial size to calcium allows for it to be absorbed by plants as a substitute for calcium (Poszwa et al. 2000; Moyen and Roblin 2010). Plants may also absorb strontium through leaves and stems, but root uptake incorporates up to 200 times more strontium (Malek et al. 2002).

Although strontium is not an essential nutrient, it can affect plant growth (Seregin and Kozhevnikova 2004; Moyen and Roblin 2010), metabolic development (Kartosentono et al. 2001), and chlorophyll amounts (Moyen and Roblin 2010), among other things. Strontium uptake in plants is dependent on soil concentration and characteristics, species, and plant organs (Collander 1941; Romney et al. 1960; Bollard and Butler 1966; Guha and Mitchell 1966; Garten et al. 1977; Morley and Pilbeam 2006), and is absorbed through the roots, leaves, and other aerial plant parts (Capo et al. 1998). Most plants discriminate against the incorporation of strontium in favour of calcium in aerial plant plants, with decreasing strontium concentrations from root to leaf (Menzel and Heald 1955; Russel and Squire 1958; Elias et al. 1982); however, the tops of plants often have the highest concentrations of strontium (Kabata-Pendias 2001). Although the concentration and distribution of calcium and strontium between and within plants may vary, plants do not discriminate between strontium ions ($^{87}$Sr and $^{86}$Sr) during uptake (Graustein 1989; Green et al. 2004) and
any fractionation within the plants is marginal and can be corrected for during mass spectrometry (Pett-Ridge et al. 2009).

Poszwa et al. (2002) found that plant leaves had narrower $^{87}\text{Sr}/^{86}\text{Sr}$ ratio ranges than those of bulk soil, meaning that plants provide a more accurate average of biologically available strontium (see section 2.3.3).

2.3.3 Strontium -87 in the food chain and biologically available $^{87}\text{Sr}/^{86}\text{Sr}$

Strontium, when consumed by animals from either a dietary source or water, behaves similarly metabolically to calcium (Nielsen 1986). Although strontium absorption has been extensively studied since the inception of the nuclear era (see: MacDonald et al. 1951; Jowsey et al. 1955; Lough et al. 1963; Rosenthal and Harbor 1965; Kostial et al. 1969), its uptake is not completely understood, with factors such as increased magnesium (Ebel and Comar 1968), age (Nielsen 1986), calcium content in the dietary source (United States Department of Health and Human Services 2001), and inclusion of fibres such as cellulose (Momcilovic and Guden 1981), affecting strontium absorption.

In mammals, calcium is preferentially absorbed over strontium (Miller 1989), with 40-80% of ingested calcium, but only 20-40% of ingested strontium, utilised by the organism (Spencer et al. 1960, 1973; Kostial et al. 1969). However, like calcium, over 99% of absorbed strontium is deposited within bone and tooth (Tomza et al. 1983). Recent research (Oliviera et al. 2012) in mature animals suggests that strontium is not deposited homogeneously throughout the skeleton, but is incorporated in greater concentrations in some elements relative to others.

Perhaps the predominant factor affecting strontium absorption and metabolism is age (Nielsen 1986). Younger, near infantile mammals appear to discriminate less against strontium, utilising it with almost as much efficiency as calcium within rapidly
growing tissues (Comar et al. 1955; Palmer and Thompson 1964; Rosenthal and
Harbor 1965). It is also found in almost equal quantities within different tissue types
in younger mammals (Rosenthal and Harbor 1965). However, as an animal ages,
discrepancies between strontium concentration in different organs and tissues become
more apparent (Rosenthal and Harbor 1965).

The Sr/Ca content within animals is also greatly dependent upon their position
in food chains (Elias et al. 1982); this is due to the process of biopurification (Elias et
al. 1982). Plants have higher Sr/Ca ratios than animals (Nielsen 1986), and thus
supply the food chain with the initial Sr/Ca ratio. As an animal consumes a dietary
source or water, its metabolism preferentially selects for calcium from the nutrient
media to incorporate into bone (Elias et al. 1982). The initial Sr/Ca ratio continues to
decrease as it progresses through the food chain by a factor of five per trophic level
because the metabolism of organisms will preferentially select for calcium from the
nutrient media derived from the prey animal (Elias et al. 1982). Thus, in a simple
food chain, Sr/Ca ratios continue to decrease from plants to carnivores.

The variance of Sr/Ca between individuals at the same trophic level is also
reduced as one moves up the food chain (Elias et al. 1982; Burton et al. 1999, 2003).
This variance is expressed as a coefficient of variation, from 145% in soils to 20% in
carnivores (Bentley 2006). Strontium isotopic composition is also affected by
changes in trophic level. As herbivores browse, they consume a variety of plants with
a range of $^{87}\text{Sr}/^{86}\text{Sr}$ compositions, in effect averaging out the values (Hall-Martin et al.
1993; Koch et al. 1995); this range is further reduced as predators consume prey with
varying $^{87}\text{Sr}/^{86}\text{Sr}$ compositions. Analysing the $^{87}\text{Sr}/^{86}\text{Sr}$ compositions of plant and
animal tissue is a measure of biologically available $^{87}\text{Sr}/^{86}\text{Sr}$ (Sillen et al. 1998).
Biologically available $^{87}\text{Sr}/^{86}\text{Sr}$ represents strontium that exits the lithosphere and
enters the biosphere, being absorbed and taken up by plants and animals (Sillen et al. 1998). This ratio represents an average of locally available strontium isotope fluxes. For example, plant $^{87}\text{Sr}/^{86}\text{Sr}$ compositions can be a mixture of bedrock, groundwater, rainwater, and aerosol strontium sources (Graustein 1989). The $^{87}\text{Sr}/^{86}\text{Sr}$ of animal tissue presents an even more accurate measure of the local $^{87}\text{Sr}/^{86}\text{Sr}$ because animals consume a variety of different sources within the area, averaging out the more restricted $^{87}\text{Sr}/^{86}\text{Sr}$ compositions of plants (Koch et al. 1995).

$^{88}\text{Sr}/^{86}\text{Sr}$ fractionation has been reported during biological processes in some plants (de Souza et al. 2010) and corals (Fietzke and Eisenhauer 2006; Ruggeberg et al. 2008), although significant fractionation of $^{87}\text{Sr}/^{86}\text{Sr}$ is unlikely due to the slight mass difference between strontium-$^{87}$ and strontium-$^{86}$.

### 2.4 Strontium -$^{87}$ in humans

#### 2.4.1 Strontium metabolism

Strontium is a trace element with no confirmed essential function within humans (Pais and Jones 1997: 135). However, research suggests that it stimulates bone formation (Canalis et al. 1996) and decreases bone resorption (Su et al. 1992), thus garnering clinical interest as a potential treatment in degenerative bone diseases such as osteoporosis (see: Shorr and Carter 1952; Marie 2003; Meunier et al. 2009; Reginster et al. 2012). In addition, it may partially fulfill calcium requirements in some enzymatic systems (MacDonald 1975; Peachell and Pearce 2012; Thomsen et al. 2012). Although strontium toxicity in humans has not been reported, some clinical studies have suggested that increased dosages may have negative effects on certain mechanisms, such as bone mineralisation (see: Jones 1938; Bartley and Reber 1961; Doberenz, Weber, and Reid 1969; Morohashi, Sano, and Yamada 1994; Jonville-Bera et al. 2009).
Strontium enters the human body primarily through the consumption of food and water and is managed similarly to calcium (Dahl et al. 2001): it is absorbed by the gastrointestinal tract, incorporated predominantly (99%) in the hydroxylapatite component of the skeleton, and excreted primarily in urine (Dahl et al. 2001). The uptake of non-essential trace elements such as strontium may be dictated by apposition, resorption, and surface and diffuse exchange mechanisms (Marshall 1969; Marshall et al. 1973; Newton et al. 1985; Rowland 1964), and mediated by individually-specific factors such as age (Nielsen 1986), sex and disease (D’Haese et al. 2000), dosage (Pan et al. 2009), and dietary content (Momcilovic and Guden 1981), among others. Strontium concentrations are highest in the iliac crest, mandible, and cranium relative to other skeletal elements (including teeth), and vary amongst single elements as well (Oliviera et al. 2012).

Although strontium is not an essential nutrient, it is absorbed due to its physical similarities to calcium – the radial size of a divalent strontium cation (Sr$^{2+}$) is 1.13 Å, which is similar to that of calcium (Ca$^{2+}$ [99 Å]) (Dahl et al. 2001). This similarity allows for strontium to substitute for calcium, although the body preferentially selects for calcium and strontium incorporation is limited to a theoretical maximum of one strontium ion for every ten calcium ions (Dahl et al. 2001). Like calcium, over 99% of absorbed strontium in the human body is concentrated in the skeleton (Dahl et al. 2001), with the remaining 1% being taken up by soft tissue and blood (Nielsen 1986).

2.4.2 Strontium in bone and mechanisms of Ca-substitution

Bone is a living tissue and thus is constantly remodelling both its organic and inorganic phases (Jowsey 1971). As such, the strontium within the skeleton is continually removed and replaced by strontium absorbed from nutrient media
throughout the remodelling process. However, remodelling is a complex process affected by multiple factors, the interplay of which is not understood completely and is currently under research (Maïmoun and Sultan 2011), and thus can occur at different rates depending on: bone type (Bjørnerem et al. 2011; Dahl et al. 2001; Tsubota et al. 2009), element (Boivin et al. 1996; Tsubota et al. 2009), pathology (Eriksen et al. 1990; Feng and McDonald 2011; Khosla and Riggs 2005), age (Andersen et al. 2009; Riggs et al. 1982; Seeman 2009; Schnitzler et al. 2009; Weaver et al. 1996), health (Dahl et al. 2001; Maïmoun and Sultan 2011; Feng and McDonald 2011), sex (Feng and McDonald 2011; Garnero et al. 1996; Khosla et al. 1998; Raisz 1988; Riggs et al. 1982; Riggs et al. 2002; Weaver et al. 1996), and ethnicity (Cosman et al. 2000; Gundberg et al. 2002; Tanaka et al. 1981).

The incorporation of strontium into hydroxylapatite occurs by one of two processes as it substitutes for calcium: (1) a rapid incorporation in which “blood strontium [is] deposited by ionic exchange, surface adsorption, and preosseous protein binding,” (Gedalia 1975:127); (2) strontium is incorporated much more slowly into the hydroxylapatite crystal lattice during bone formation (Gedalia 1975; Cazalbou et al. 2002). The first mechanism is much more common, with strontium predominantly adsorbed onto the surface of the hydroxylapatite crystal lattice (Cazalbou et al. 2002), and a much smaller amount incorporated into it (Rokita et al 1993). However, both processes are supplied primarily from strontium in the blood (Gedalia 1975). In addition, like strontium absorption from nutrient media, strontium incorporation into hydroxylapatite may also be a function of age; Gedalia (1975) found no mean increase of strontium in fetal femur and tooth ash despite increased strontium in the nutrient media. However, this is most likely due to the reduced periods of calcification in foetuses compared with those of adults (Gedalia 1975). Furthermore, in synthetic
experiments (Likins et al. 1961), older, larger hydroxylapatite crystals showed a discrimination against strontium in favour of calcium.

Bone types too, in addition to specific elements, show discrepancies in strontium concentrations (Dahl et al. 2001). The formation of new cancellous and cortical bone is characterised by a higher strontium concentration than is older, more mature bone, with a 2.5 fold higher content in new cancellous bone and a 3-4 fold increase in new cortical bone (Dahl et al. 2001:448). In addition, strontium has a longer residence time when incorporated into the hydroxylapatite crystal structure of bone, and in particular, that of cortical bone, than it has when only adsorbed onto surface structures (Montgomery 2002). In general, cancellous bone remodels more quickly than cortical bone, the latter capable of taking upwards of 10 years to completely turnover whereas the former may completely remodel within a few years (Hill 1998; Jowsey 1961).

2.4.3 Enamel formation and strontium in enamel

Enamel is the hardest, most mineralised tissue in the human body, and its primary functions are to protect dentine and pulp and to enable sustainable mastication (Avery 2002). Its hardness is a function of its composition: enamel’s primary constituent is hydroxylapatite, with minor inclusions of carbonates and other trace elements, that all together form a tissue that is nearly 99% inorganic (Hoppe et al. 2003).

Amelogenesis (enamel formation) begins during the sixth week of embryonic life (Avery 2002, with permanent dentition forming from buds that stem from the enamel organs of deciduous teeth (Young et al. 2006). Although the enamel of permanent teeth is acellular, during amelogenesis the developing tooth has a variation of different cell types and is rich in cellular substances and proteins (e.g.,
glycosaminoglycans) which contribute to the growth of the tooth and enamel (Young et al. 2006). This more organic composition of enamel during development is steadily replaced during the final stages of amelogenesis as ameloblasts (enamel-forming epithelial cells) form columns of organic matrix to be progressively mineralised by inorganic hydroxylapatite, carbonates, and trace elements as the enamel matures (Young et al. 2006). These mineralised enamel rods are the basic structural units of teeth (Avery 2002), running parallel to the long axis (Fernandes and Chevitarese 1991) and extending from the dental-enamel junction to the enamel surface (Avery 2002).

Strontium isotopes adsorbed onto the surface of hydroxylapatite crystals or incorporated into them become a permanent, static feature of enamel once amelogenesis is complete (Balasse 2002). Mature enamel is acellular and therefore incapable of remodelling or repair (Avery 2002). Therefore, the $^{87}\text{Sr}/^{86}\text{Sr}$ composition of enamel, is a reflection of the $^{87}\text{Sr}/^{86}\text{Sr}$ composition absorbed from the nutrient media in an organism during amelogenesis (Balasse 2002). In humans, enamel formation begins during week six of embryonic development (Avery 2002), and terminates by 16 years of age (Chandra et al. 2004).

$^{87}\text{Sr}/^{86}\text{Sr}$ compositions can vary between tooth enamel within the same organism because amelogenesis occurs at different stages of development for different teeth (Chandra et al. 2004). If the local $^{87}\text{Sr}/^{86}\text{Sr}$ composition were to change at the onset of or during the amelogenesis of a sequential tooth, the enamel of that tooth would have a dissimilar $^{87}\text{Sr}/^{86}\text{Sr}$ composition to that of the tooth that had developed before it. It is for this reason that the strontium isotopic composition of teeth can be used to investigate human mobility (reviewed in Chapter 3). In addition, intra-tooth variations in $^{87}\text{Sr}/^{86}\text{Sr}$ compositions may also occur. If the strontium isotopic
composition in the nutrient media changes during the amelogenic development of a single tooth, the sections of the tooth accreted after this change will reflect the new isotopic composition (Dolphin et al. 2005).

2.5 Diagenesis

Diagenesis is a post-depositional process in which components of the burial environment alter the original chemical composition of bone and teeth (Brown and Brown 2011; Sillen 1989). It can occur due to a multitude of environmental factors including, but not limited to: water and oxygen availability, free ion availability, soil pH, temperature, and the presence of soil flora, fauna, and microorganisms (Grupe 2007; Hedges 2002;). Intrinsic factors of hard tissue such as porosity, crystallinity, and bone size (Hedges 2002; Nielsen-Marsh and Hedges 2000) can also affect diagenesis. It is a complex and multi-faceted process that affects both the inorganic and organic phases of hard tissue (Nielsen-Marsh et al. 2000) and, due to the chemical uniqueness of each depositional environment, does not adhere to a generalised pattern of development nor occur at a set rate; however, studies have shown correlations between different diagenetic processes in similar site environments (see Bocherens et al. 2008; Fernández-Jalvo et al. 2010; McNulty et al. 2002; Nielsen-Marsh and Hedges 1997; Sillen and Parkington 1996; Tütken et al. 2008;).

Due to the different structural and chemical components of bone and enamel, diagenesis affects both of these hard tissues differently (Ezzo 1992; Price 1989). Bone, which is relatively porous and comprised of ~30% (dry weight) organic matter arranged around and within small hydroxylapatite crystals, is more susceptible to diagenetic processes than enamel (Hoppe et al. 2003); organic matter is more easily destroyed by diagenesis, and this chemical disarticulation allows for an increase in porosity, which in turn further weakens the structural component of the bone
Furthermore, the greater CO$_3$ content of bone allows for a decrease in crystallinity and an increase in apatitic solubility (LeGeros 1981; LeGeros and LeGeros 1993). In addition, dentine, like bone, is also comprised of ~30% organic matter, and is thus susceptible to diagenetic processes (Dauphin and Williams 2004). Enamel (Ca$_{10}$(PO$_4$)$_6$(OH)$_2$), conversely, is nearly 99% inorganic, less porous (Hoppe et al. 2003), has high crystallinity and a low solubility of apatite (LeGeros 1981), making it more resilient to diagenetic change (Hoppe et al. 2003; Legeros 1981). This thesis is concerned only with $^{87}$Sr/$^{86}$Sr compositions in enamel, and therefore only diagenetic processes pertaining to enamel strontium concentrations will be discussed.

Despite the more resistant constitution of enamel over other hard tissues, diagenetic changes in structure and chemical composition can occur (Dauphin and Williams 2004; Kohn et al. 1999; Nelson et al. 1986; Schoeninger et al. 2003; Sillen 1986; Zazzo et al. 2004). Diagenetic strontium can affect the original strontium isotopic composition of enamel in four manners: it can be adsorbed onto surface enamel and into microcracks; participate in pore filling; be incorporated during the recrystallisation or remineralisation of hydroxylapatite; or substitute for calcium in a direct exchange in the original hydroxylapatite crystals (Nelson et al. 1986). Hoppe et al. (2003:22) removed ≥95% of diagenetic strontium in their enamel samples by washing them with weak (≤1.0 N) acetic acid. However, this method will only remove adsorbed strontium, not that incorporated by exchange or substitution into the crystal enamel structure (Nelson et al. 1986; Sillen 1986; Tuross et al. 1986).

Methods such as Fourier-Transform infrared (FTIR) spectroscopy and FT-Raman spectroscopy are able to detect changes to the crystalline structure of enamel and therefore determine whether or not diagenetic alteration has occurred.
In general, researchers do not independently test strontium preservation after pretreatment. Hoppe’s (2003) experiments (see above) as well as the biochemical resilience of enamel to diagenetic change are cited frequently in support of foregoing diagenetic testing (e.g., Evans et al. 2006; Nafplioti 2008; Price et al. 2010; Shaw et al. 2010; White et al. 2005; Wright 2005). However, some studies have employed different techniques in the evaluation of diagenesis to assess the integrity of their samples for strontium isotope analysis. For example, a commonly used method is to compare the chemical composition (e.g., the calcium-phosphorous ratio) of archaeological samples with those of modern skeletal material (e.g., Knudson and Price 2007; Price et al. 1994; Sillen 1989). Furthermore, the identification of secondary minerals (e.g., Fe, Mn, Si, Al) or rare earth elements (e.g., U, F) in tooth or bone by ion or electron microprobes suggests that a sample was contaminated post-depositionally (Kohn et al. 1999; Wright et al. 2010). In addition, some studies have compared the Sr concentrations of modern and archaeological teeth – archaeological samples with increased amounts of Sr are suggested to be diagenetically altered (e.g., Budd et al. 2000).

2.6. Summary

The pathway of $^{87}$Sr from bedrock to human enamel is complex and unique, and although measurement of the $^{87}$Sr/$^{86}$Sr composition is possible, elucidating the geographic origin of $^{87}$Sr can be difficult - it is confounded by many different factors which affect the final strontium isotopic ratio in enamel. An understanding of these factors and the magnitude of their influence on the $^{87}$Sr/$^{86}$Sr composition is necessary for proper analysis of the measurement.
The next chapter reviews the relevant literature for this thesis with a focus on the development of strontium isotope analysis, early applications of the technique to archaeological studies, refinements to the method, and its use in Maya archaeology.
Chapter 3: Literature Review

This chapter examines briefly the concept of mobility in archaeology and how it is determined and used to investigate other aspects of past behaviour. Traditionally, proxies, such as the occurrence of foreign architecture or ceramics, have been used to infer mobility or the exchange of ideas. Strontium isotope analysis is introduced as a bioarchaeological method capable of directly measuring mobility and a technique that has refined or refuted many conjectures based on the use of proxies to infer mobility. Following, the development of strontium isotope analysis is discussed as well as some of its early applications to archaeology. Refinements to the technique, as well as the wide range of archaeological questions that it has been used to answer are explored before the chapter becomes more focused on the application of strontium isotope analysis in Mesoamerica. Ranging from studies on specific individuals to whole populations, the studies examined exhibit the utility of this method when used in an area with variability in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The chapter concludes with a discussion of the strengths and weaknesses of strontium isotope analysis and explores some of the techniques researchers have used to refine the method.

3.1 Mobility in archaeology

The concept of mobility in archaeology generally (see Chapter 1) refers to the movement of an individual or group from one area to another, regardless of the amount of time spent in the new location. Mobility is frequently studied to determine and evaluate varying facets of past life including, but not limited to: seasonality (e.g., Akazawa 1980; Burchell et al. 2013; Hofman et al. 2006; Pike-Tray and Cosgrove 2002; Plug 1998; Riley 2008; Rival et al. 2009; Simmons and Nadel 1998; Surge and Barrett 2012; van Neer et al. 2004), migration (e.g., Ahlstrom 1995; Chen et al. 2008; Mandryk et al. 2001; Naum 2009; Raczek 2012; Shaw et al. 2009; Snow 1995; Su et
Archaeologists examine many diverse lines of evidence to understand past human mobility; one of the most commonly employed methods is the study of functional and aesthetic styles foreign to an archaeological site (e.g., Bar-Yosef and Belfer-Cohen 1991; Camilli 1989; Kelly and Todd 1988; Naum 2009; Kidder 1946; Thompson 1943; Willey et al. 1967). Although the presence of foreign material remains may be indicative of cultural diffusion or trade, archaeologists often consider multiple lines of evidence before inferring mobility. For example, the sudden proliferation of Baltic ceramics in medieval Denmark has been studied as an indicator of immigration and not cultural diffusion because medieval chronicles, Slavic-sounding place names, and burial finds support a theory of immigration (Naum 2009).

Site size and population can also be used as indicators of human mobility. By studying architectural remains and site size, researchers can infer population size, which can then be used to examine mechanisms of population growth. Archaeologists argue that the rapid increase in population size seen at the Mesoamerican city of Teotihuacán happened too quickly to have occurred without the aid of immigration as a growth mechanism (Cowgill 1992; Sanders 1991). Similarly, the rapid population growth at Tikál in Guatemala within a short time span has also been examined as a function of immigration from rural and distant cities (Wright 2005a).
However, these methods serve as proxies for individual/population movement and are not direct evidence for human mobility in the past. Bioarchaeological data is a source of direct evidence for ancient human mobility because certain behaviours leave biochemical markers in the human skeleton. By measuring these biochemical indicators, archaeologists can infer mobility from direct lines of evidence rather than through proxy methods.

3.2 The development of strontium isotope analysis as a bioarchaeological method

Bioarchaeological methods allow researchers to examine a direct cause-and-effect relationship between past behaviour and individual biochemical characteristics (Buikstra 1977). Because $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are geological in origin and have a high degree of variability that can be tied to discreet geographic regions (Graustein 1986), it is possible to use this biogeochemical data to reconstruct human mobility.

Strontium isotope analysis was not initially created as an archaeological method. Aldrich and colleagues (1953) first observed differences in the mineral isotopic abundances of strontium while analysing the strontium content of mineral sources. Determining that these differences could be utilised to date geologic materials, this method was quickly recruited to understand formation processes (see Gast 1960; Gast et al. 1964; Hedge 1966; Leeman 1971; Peterman 1970; Pushkar 1968) and the composition of seawater throughout time (Burke et al. 1982; Peterman et al. 1970). In the early 1980s, the method was adopted into use in ecology to monitor atmospheric inputs of fly ash to plants and soil (Hurst and Davis 1981; Straughan et al. 1981) and forest canopies (Gosz et al. 1983).

Strontium would not become an element of study in biological fields until an influx of interest in the biological role of organismal strontium was generated in the mid 1960’s after Howard Odum’s (1951, 1957) examination of strontium cycling in
ecosystems and strontium’s relationship with calcium in organisms. Following Odum’s publications, Toots and Voorhies (1965) suggested that the Sr/Ca ratio in organisms could be examined in fossils to determine diet, and their study was quickly followed by others also examining the viability of analysing strontium within fossil and prehistoric specimens (see Boaz and Hampel 1978; Brown 1973; Parker 1968; Parker and Toots 1970). Brown (1973), Gilbert (1975), Schoeninger (1979a, 1979b), and Sillen (1981a, 1981b) were among the first to apply the technique to archaeology as a novel approach to study past human diet.

Jonathan Ericson, drawing from the relative successes of strontium isotope analysis in geochemical and ecological fields, as well as the recent interest in organismal strontium in biology, first applied strontium isotopic analysis to archaeology in 1985. Due to the potential geographic specificities of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and strontium’s incorporation into the skeleton, he suggested that the $^{87}\text{Sr}/^{86}\text{Sr}$ compositions in archaeological tooth and bone could be studied to provide information on warfare, marital residence, territoriality, migration, exchange of food, and animal ecology (Ericson 1985). Ericson cautioned that a lack of geographical $^{87}\text{Sr}/^{86}\text{Sr}$ variation, diagenetic contamination, mobility within the study population, consumables from locales with different $^{87}\text{Sr}/^{86}\text{Sr}$ compositions, and the incorporation of high-strontium foods within the diet could confound the $^{87}\text{Sr}/^{86}\text{Sr}$ analysis (Ericson 1985). Despite a small sample size, Ericson’s pilot study suggested that strontium isotopic compositions within archaeological tooth and bone could be measured to provide meaningful data on past human mobility.

Following Ericson’s (1985) publication, a number of researchers used strontium isotope analysis to examine residence patterns in South Africa (Sealy et al. 1991, 1995), Central Europe and Germany (Horn et al. 1994; Grupe et al. 1997; Price
et al. 1998, 2001) Mexico (Price et al. 2000), and Arizona (Ezzo et al. 1997; Ezzo and Price 2002; Price et al 1994). As with other novel scientific methods gaining popularity, studies were undertaken to refine the technique, with particular attention being given to potential diagenetic contamination. These early studies on diagenesis (Sealy et al. 1991; Sillen 1986) suggested that biogenic strontium could be preserved and isolated for study in skeletal material, and demonstrated that acid pretreatment could remove ≥95% of diagenetic strontium in enamel, but was far less effective at removing it in bone (Hoppe et al. 2003). Dentine was also found to be less reliable than enamel (Budd et al. 2000).

3.3 Archaeological uses of strontium isotope analysis

The implementation of these new refinements and a growing confidence in the technique saw a multitude of strontium isotope analyses conducted on bioarchaeological material from many different areas and time periods (e.g., Bentley et al. 2009; Evans et al. 2006; Knudson and Buikstra 2007; Nafplioti 2011; Nystrom et al. 2011; Perry et al. 2011; Price et al. 2006; Shaw et al. 2009; Sjögren and Price 2013; Soichiro et al. 2012; Stojanowski and Knudson 2011; Turner et al. 2012; Wright 2005a,b).

In addition to providing results that are robust without support from additional techniques, archaeologists use strontium isotope analysis to corroborate or refute arguments for mobility based on more traditional techniques (e.g., foreign ceramic and architecture styles [Sharer and Gifford 1970; Thompson 1943]). For example, Wright et al.’s (2010) strontium isotopic data from decapitated skulls at Kaminaljuyu supported Kidder’s (1946) argument that the skulls belonged to simultaneously-deposited victims from different regions while refuting Weiss-Krejci’s (2003) suggestion that the individuals had been lineage members deposited sequentially.
The questions that researchers sought to answer by using the technique also became more complex and detailed as strontium isotope analysis began to be used in more creative ways. For example, strontium isotope analysis has been used to investigate: whether differences in ritual tooth ablation types could distinguish between locals and immigrants at a Japanese site during the Late-Final Jomon period (Kusaka et al. 2012); and the migratory behaviour of Jonzac Middle Palaeolithic reindeer and whether this mobility could have influenced Neanderthal hunting strategies (Britton et al. 2011). Strontium isotope analysis has also been used in conjunction with other techniques in order to gain a more comprehensive understanding of the details of past lives. For example, headless Roman burials at York, Northern England had strontium and oxygen isotopic values that identified many as non-locals and revealed that, at this site, similar burial rites were not necessarily related to common geographic origin (Müldner et al. 2011).

3.4 Application of strontium isotope analysis in Mesoamerica

Migration and mobility in Mesoamerica have been a subject of interest in archaeology throughout the 20th century; archaeologists have used architectural, epigraphic, and ceramic data to argue for contact between states and for population migration (e.g., Borhegyi, 1971; Kidder et al. 1946; Reents-Budet et al. 2004; Sharer and Gifford 1970; Sharer et al. 2005; Thompson 1943, 1945; Willey et al. 1967). However, these foreign cultural elements are used as proxies for the examination of mobility in the Maya subarea and do not constitute conclusive, direct evidence for mobility. For example, at the highland centre of Kaminaljuyu, Teotihuacán architecture and ceramics are conspicuous and led archaeologists to argue that the city had been conquered by the central Mexican state (Kidder 1946; Borhegyi 1965), or that Teotihuacán excised economic control over Kaminaljuyu (Cheek 1977). A later
strontium isotope study (Wright 2010) (this section, see below) found evidence suggesting stronger political ties with the Lowland Maya, and an indirect relationship with Teotihuacán.

In addition to the difficulties of determining mobility from non-direct methods, mobility studies in Mesoamerica are further confounded by poor skeletal preservation tied to climate and soil type (Hernández and Márquez, 2006). In general, skeletal remains are badly degraded and fragmentary and often tooth is the only material preserved; this precludes the use of most measurable genetic skeletal traits (e.g., Ricaut and Waelkens 2008) or cultural practices affecting the skeleton (e.g., dental or cranial modification [see Tiesler 2010]) to infer origin.

Strontium isotope analysis is a method well-suited to overcoming the obstacles associated with the investigation of mobility in Mesoamerica. It provides a direct line of evidence for past mobility by acquiring the biochemical signatures of ancient individuals, and it can be performed on very small amounts of skeletal tissue (e.g., samples as small as 0.023g; see Chapter 5). Due to the relative simplicity of strontium metabolism in the human body (Dahl et al. 2001), the physicochemical properties of strontium itself, and the varying geographical ranges of $^{87}$Sr/$^{86}$Sr compositions (e.g., Hodell et al. 2004), strontium isotope analysis has proven to be a robust method for determining mobility in ancient populations and individuals.

Researchers working in Mesoamerica have utilised strontium isotope analysis to examine different aspects of mobility and migration by identifying non-locals amongst ancient Maya populations, and in some studies furthering their arguments by comparing their isotopic data with archaeological evidence or with other isotope data (e.g., Price et al. 2000; Price et al. 2006; Price et al. 2008; Price et al. 2010; Price et al. 2012; White et al. 2007; Wright 2005a, 2005b; 2013; Wright et al. 2010).
Strontium isotope analysis on Maya remains was first conducted on enamel and bone samples from Teotihuacán to test the inferred non-local status of individuals interred within residential compounds exhibiting foreign architecture and ceramic styles (Price et al. 2000). This research demonstrated that many of the individuals buried within these compounds were not born locally (e.g., they had non-local enamel $^{87}\text{Sr} / {^{86}\text{Sr}}$ ratios) but they had lived in Teotihuacán for an extended period of time before their death (e.g., they had local bone $^{87}\text{Sr} / {^{86}\text{Sr}}$ ratios) (Price et al. 2000). This early study elucidated the importance of migration for the population at Teotihuacán and exhibited the usefulness of strontium isotope analysis in Mesoamerica.

After this initial study, many researchers applied this technique to address long-standing questions about mobility and migration among ancient Mesoamerican populations. For example, at Tikál, the proportion of non-local individuals was found to be high enough to suggest that migration was important to the structure and growth of the population (Wright 2005a). At Copán, the $^{87}\text{Sr} / {^{86}\text{Sr}}$ value of enamel samples from the ruler K’inch Yax K’uk’ Mo’ suggested a childhood residence of Tikál or Northern Petén, which corroborates epigraphic and iconographic evidence at the centre (Price et al. 2010). At Kaminaljuyu, skeletal strontium and oxygen isotope values were consistent with population ties to the Maya Lowlands rather than central Mexico; this contradicts the ceramic and architectural evidence that suggested strong ties with Teotihuacán (Wright et al. 2010).

Studies have also focused on the collection of $^{87}\text{Sr} / {^{86}\text{Sr}}$ ratios across geographic expanses of Mesoamerica for the establishment of baseline strontium isotope values by analysing the strontium isotopic ratios of soil, rock, plant life, water, and modern and archaeological fauna (e.g., Hodell et al. 2004; Price et al. 2008; Thornton 2011; Yaegar and Freiwald 2009). This research has produced a rich and
diverse map of strontium isotope variability across Mesoamerica. Establishing baseline/local strontium isotope values using archaeological or modern fauna is preferred because animal ratios represent an average of the locally available $^{87}\text{Sr}/^{86}\text{Sr}$ ratios throughout a region (Koch et al. 1995). These studies demonstrate that $^{87}\text{Sr}/^{86}\text{Sr}$ ratios within Mesoamerica do vary across geographic space, however not all geographic areas are isotopically unique (Hodell et al. 2004). This fact means that some non-locals could be mistakenly identified as locals (if their $^{87}\text{Sr}/^{86}\text{Sr}$ ratios overlap) and that it may not be possible to identify the exact geographical origin for all non-locals.

3.5 Strengths and weaknesses of strontium isotope analysis

Since its inception as a bioarchaeological method by Ericson (1985), strontium isotope analysis has been utilised as a direct, robust method for the identification of non-locals and as an indispensable tool in the examination of past human migration and mobility. In Mesoamerica particularly, strontium isotope analysis is becoming a widely used method amongst archaeologists. The geographic variability of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Hodell et al. 2004) is marked throughout the region which is ideal for strontium isotope analysis. The relative differences among strontium isotope ratios in different areas allow archaeologists to distinguish local and non-local individuals and also to suggest potential childhood residencies for non-local individuals.

Enamel is the most reliable tissue for strontium isotope analysis due to its resistance to diagenetic processes (Hoppe et al. 2003; LeGeros 1981) and because its formation occurs during discrete periods and it does not remodel (Young et al. 2006). Because the developmental stages of enamel formation are well-understood, researchers can sample multiple teeth from the same individual to acquire evidence for
mobility at distinct periods during childhood (e.g., Müller et al. 2003; Price et al. 2010), something that is not possible with bone.

On an atomic level, strontium’s physicochemical properties contribute largely to the usefulness of strontium isotope analysis. A heavy element, biological systems lack the energy necessary to fractionate isotopes such as $^{87}$Sr and $^{86}$Sr, meaning that there is no preferential uptake of either isotope by organisms (Capo et al. 1998). Additionally, strontium follows a relatively simple pathway from mineral deposits into biological systems (see Chapter 2), and its metabolism by mammals is comparatively straightforward – only 1% of mammalian strontium is found in soft tissue and blood (Nielsen 1986), the other 99% is localised within the skeletal system (Dahl et al. 2001). Strontium’s relatively simple metabolic pathway and the lack of fractionation between isotopes $^{87}$Sr and $^{86}$Sr result in organismal strontium isotopic ratios that can directly represent the environment.

Although a robust method for studying ancient mobility and migration, refinements to the method are still needed for its utility and for a more comprehensive understanding of past behaviour. One of the largest uncertainties of the method is the working assumption that the individuals were consuming local food and water. If individuals were consuming imported food, the local geographic $^{87}$Sr/$^{86}$Sr ratio may not be accurately represented. In environments where individuals are consuming imported food from geologically dissimilar areas, the individual strontium isotope ratios will represent a ‘hybrid ratio’ (Ericson 1985). The degree to which this ‘hybrid ratio’ reflects the local geographic $^{87}$Sr/$^{86}$Sr ratio decreases as the amount of ingested non-local food increases. Wright (2005a) found that a number of the local individuals at Tikál had slightly elevated $^{87}$Sr/$^{86}$Sr ratios when compared to the $^{87}$Sr/$^{86}$Sr ratios of local fauna. She suggested that the addition of imported salt to the diet, which has a
higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratio than that found at Tikál, was elevating the strontium isotopic ratios of the local individuals (Wright 2005a). Stable carbon and nitrogen isotope data, when existent, can be used to investigate the composition of the diet and to identify the consumption of foods that are non-local to the area. However, it may not always be discernable whether or not imported food contributed to diet.

Although in some cases it is possible to suggest potential origins for identified non-local individuals, strontium isotope analysis may be confounded by childhood mobility during dental development. For example, relocation during enamel development to an area with a different $^{87}\text{Sr}/^{86}\text{Sr}$ ratio will result in a mixing of the original and new $^{87}\text{Sr}/^{86}\text{Sr}$ ratio that will not correspond to either locale. This mixing of strontium isotope ratios cannot be determined with confidence archaeologically or biochemically. In addition, there is some geographical overlap in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios that could lead to the incorrect identification of locals or confound the determination of childhood origin.

3.6 Summary

Strontium isotope analysis is a powerful tool for bioarchaeology. As with many other bioarchaeological methods, its strength lies in its ability to evaluate biochemical markers that are the result of human behaviour. However, although very useful, it does have weaknesses: factors such as childhood mobility and the consumption of imported food can confound the data, and analyses performed on enamel are more reliable than those performed on bone.

Currently used to elucidate patterns of mobility at many different archaeological sites, analyses performed on ancient Mesoamerican samples have several foci including: expanding regional $^{87}\text{Sr}/^{86}\text{Sr}$ maps, determining the percentage of non-locals
in a population, examining the mobility patterns of elites and commoners, and evaluating the extent of mobility in the Maya subarea.

The following chapter describes the site at Minanha and its history as well as the sample used for this thesis project.
Chapter 4: Site and Sample

The ancient Maya centre of Minanha was once the focus for a small city-state located in the rugged sub-tropical north Vaca Plateau of west-central Belize (Iannone 2005:27-29). Occupied between 600 B.C.E. and C.E.1200, Minanha became one of the largest centres in the Vaca Plateau during the Late Classic period (C.E.675-810) (Iannone 2010) before entering into rapid decline one hundred years later at the beginning of the Terminal Classic (C.E. 810-900) (Iannone 2005:34). The socioeconomic and socio-political dynamics throughout its 1800 years of occupation are the research interest of the Social Archaeology Research Program (SARP), directed by Dr. Gyles Iannone. The research completed for this thesis is a component of this [SARP’s] project.

4.1 Minanha

4.1.1 Geographical context

Minanha is located in the Maya subarea (see Figure 4.1), a component of the Mesoamerican culture area (Adams 2005) that includes the Yucatán Peninsula and stretches from western Honduras and El Salvador to southern Mexico (Healy and Blainey 2011). The Maya lowlands are subdivided into three constituents (southern, central, and northern) (see Figure 4.1) and encompass the northern regions of Guatemala, Belize, and the Yucatán (Sharer and Traxler 2006).

The north Vaca Plateau (see Figure 4.2) is a Cretaceous limestone and dolomite shelf deposited over an earlier formation of slates and sandstones (Alt 1995) 300m-600m above sea level (Milner 1999: Figure 3). Like most karstic formations, it is marked by escarpments and interceding valleys, the consequence of northeast and eastward faults that run towards the coast (Dunning et al. 2002). Sub-tropical and
Figure 4.1. Map of the Maya subarea displaying a few key centres discussed in this thesis. Dashed lines delimit the Maya Highlands (area between the lowermost dashed lines), Southern and Central Lowlands (area encompassed by the upper and middle dashed lines), and Northern Lowlands (area above the uppermost dashed line). Map modified from Brown and Witschey (2008), retrieved from: http://mayagis.smv.org/maps_of_the_maya_area.htm.

tropical rainforests dominate the region with deep, fertile soils permitting dense floral growth in the dry valleys (Iannone et al. 2010; Polk et al. 2007; Reeder 1996).

There is limited surface water in and around Minanha due to the lack of rain during the dry season and due to the permeability of limestone (Alt 1995), which drains water into seasonal fluvial systems or groundwater deposits (Dunning et al. 2002). The Maya of Minanha employed a number of strategies in order to secure
year-round access to water sources, including: the modification of natural reservoirs, called *aguadas*, the largest of which was the Mayo Aguada, situated one kilometre north-east of the epicentre (Primrose 2003:91); the exploitation and occasional modification of permanent and seasonal springs (Primrose 2003:84-93,97); and the

**Figure 4.2.** Map of the Vaca Plateau (grey) with Minanha and surrounding area highlighted. Modified from Iannone (2005:28).
utilisation of sartenejas, natural basins that hold water, as tertiary sources (Primrose 2003:107).

Palaeoclimate data from the Macal Chasm, located in west-central Belize, suggests that the past 3300 years have been characterised by a sporadic oscillation between wet, warm periods and drier periods, in addition to severe droughts (Webster et al. 2007). Many of these drier intervals coincide with periods of decreased populations and activity; the most marked prolonged dry period in the 3300-year climatological record occurred between C.E. 700-1135, which corresponds to the periods associated with the “Classic Maya Collapse” (Webster et al. 2007).

Sub-tropical to tropical rainforest growth characterises the central lowlands, contributing to the unique and varied soil types of the area (Beach et al. 2011). Limestone and carbonate parent materials, high rainfall during the wet season, and a marked dry season have also contributed to the formation of thin rendoll, alfisol, and inceptisol soils on the steep slopes of escarpments and deeper histosols and vertisols in the intervening depressions (Beach 1998; Fernandez et al. 2005; Beach et al. 2006; Webb et al. 2007; Johnson et al. 2007). Although fertile, the soils of the area are nitrogen- and phosphorous-deficient (Murtha 2002) as well as highly erodible and porous, allowing water to drain easily through the soil profile (Beach et al. 2008).

4.1.2 Excavations and site history

In 1927, five years after its discovery by a tree gum farmer, the British Museum undertook a brief, six-day archaeological investigation at the site of Minanha (Iannone 1999). Subsequent to this, the site was lost for seventy years until being relocated in 1998 by Gyles Iannone after a request in 1997 from the Department of Archaeology in Belmopan, Belize to try to find the site (Iannone 1999). Since relocating the site, SARP has conducted a long-term investigation of the socio-
political and socioeconomic dynamics at Minanha by implementing an “archaeology of community” approach (Iannone 1999, 2006), which has ultimately contributed to the broader question of the Maya collapse.

SARP’s excavations at Minanha were conducted in three phases, each with distinct goals. Phase I (1999-2005) excavations focused on the epicentre (see Figure 4.3), the seat of royal power, and explored Minanha’s “rise and fall” from the perspective of the royal court (Iannone 1999, 2006c; Iannone et al. 2007, 2010). Phase II (2006-2009) excavations were conducted in the two settlement zones of Minanha’s support population – the site core (see Figure 4.3), a 1 km² area immediately encompassing the epicentre and comprised of 39 settlement units and civic-ceremonial complexes (Longstaffe 2009); and the Contreras Valley (see Figure 4.4), a productive agricultural area with 98 settlements located 1.5 km southeast of the epicentre (Macrae 2010). Phase III excavations focused on the minor centres located in close proximity to Minanha in order to elucidate their relationships with the site during its period as a key centre in the north Vaca Plateau (Iannone et al. 2007, 2010). In addition, further excavations in the epicentre along with cave archaeology (Moyes and Awe 2010) and the study of past climate from cave sediments and speleotherms (Brook and Akers 2010; Polk 2010) were also components of Phase III. SARP’s excavations and research at Minanha have provided a detailed understanding of the site’s history (summarized in Table 4.1 and detailed below).

Located on a high hilltop at the confluence of four major valley passes and at the junction of three resource zones, Minanha was in an area of economic, strategic, and military importance (Iannone 2005), but would not assume prominence until the Late Classic period, one thousand years after it had first been settled by small
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<thead>
<tr>
<th>Chronological Period</th>
<th>Time Period</th>
<th>Site Development</th>
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<tr>
<td>Late to Terminal Preclassic</td>
<td>400 B.C.E.-C.E. 250</td>
<td>Early development and growth of population; early agriculture and terrace construction.</td>
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<tr>
<td>Early Classic</td>
<td>C.E. 251-550</td>
<td>Expansion of community and agricultural terraces; increasing development in periphery.</td>
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<tr>
<td>Middle Classic</td>
<td>C.E. 551-675</td>
<td>Significant increase of community; increasing social stratification; further development in periphery.</td>
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<tr>
<td>Late Classic</td>
<td>C.E.676-810</td>
<td>Development of epicentral royal court complex; largest degree of social stratification; expansion of water management systems and agricultural terraces.</td>
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<tr>
<td>Terminal Classic</td>
<td>C.E.811-900</td>
<td>Demise of royal court; &quot;Maya collapse&quot;; long-standing family groups remain.</td>
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<tr>
<td>Early Postclassic</td>
<td>C.E.901-1200</td>
<td>Small groups remain at site.</td>
</tr>
<tr>
<td>Late Postclassic</td>
<td>C.E.1201-1525</td>
<td>Small groups remain at site.</td>
</tr>
</tbody>
</table>

Table 4.1. Chronology and site development at Minanha. Borrowed with permission from Stronge (2012:104).

pioneering populations (Iannone 2005). Minanha was first occupied by small populations during the Late Middle Preclassic (600 B.C.E.- 400 B.C.E.) at what would later become the site’s epicentre (Iannone 2005).

The earliest recovered architecture dates to the Terminal Preclassic (C.E. 100-250). Beginning in the late Terminal Preclassic or early portion of the Early Classic (C.E. 250-550), the inhabitants at Minanha began to construct agricultural terracing, which coincided with increases in population and social complexity (Iannone and Schwake 2010; Macrae 2010; Mosher and Seibert 2006; Zehrt 2006).

During the Late Classic period (675-810 C.E.), Minanha developed into perhaps the most important centre of the north Vaca Plateau (Iannone 2005, 2010). This Late Classic emergence as a powerful centre was potentially made possible by the diminishing authorities of Caracol and Naranjo, two large and influential neighbouring centres (Iannone 2005, 2010). Minanha occupied a location roughly equidistant between the two (25 km), placing it in an internal frontier zone.
Figure 4.3. Minanha epicentre (inner dashed circle) and site core (area outside of epicentre). Modified from original, image courtesy of SARP.

Figure 4.4. Map of Minanha proper (Zone 1) and periphery (Zone 2 [Contreras Valley]). The minor centre of Waybil is indicated to the west. Image courtesy of SARP, modified from original.
(Iannone 2005; see Kopytoff 1987, 1999) that, during this period of decentralisation, allowed for its development into an influential, but small, city-state (Iannone 2005). Minanha’s position within the internal frontier zone of Caracol and Naranjo and in a larger region dominated by the hegemonic powers of Tikal and Calakmul most probably influenced its political and military allegiances, as well as its rapid rise to prominence and swift decline (Iannone 1999, 2003, 2005, 2006, 2010).

This period of sustained growth is marked by an intensive building effort to construct a 9.5 ha court complex of elite residential compounds, plazas, and courtyards encircled by 39 ha of civic ceremonial complexes and settlements (Iannone 2005). The new Minanha elites sought to consolidate their authority by emulating the symbolism of kingship at larger centres: the epicentre adopted the cosmologically-based civic plan of Calakmul and Caracol, including all of the buildings associated with a royal court (Iannone 2005; see Grube 200:556) and numerous stelae were also erected (Iannone 2005, 2010). Iannone (2003, 2005) has suggested that nobles from Caracol, perhaps exploiting the decentralisation in this region, founded the royal court at Minanha. This royal court successfully integrated the existing power structures into their regime (Schwake and Iannone, 2010) and applied the recognised Caracol symbolism of kingship at Minanha (MacDougall and Gray, 1999; Iannone 2005, 2010).

In order to support this centre of growing influence, Minanha’s peripheral population (i.e., the individuals who farmed the land surrounding the site core) increased markedly during the Late Classic, and an extensive agricultural terracing program was implemented to extend the terraces to the majority of the hills and valleys surrounding Minanha (Iannone 2010, Macrae 2010). In addition, the minor centre of Waybil, located 2 km south of Minanha, may have fallen under Minanha’s
influence as well (Sam Connel, personal communication, 2001, as cited in Iannone 2010).

Minanha remained an influential centre for only a century before entering into a period of rapid decline (Iannone 2005, 2010). During the Terminal Classic (C.E. 810-900), along with a cessation of elite construction projects, the court complex was abandoned, the royal residential rooms and courtyard were methodically filled in and buried (Iannone 2005), and stelae and stucco façades were destroyed (MacDougall and Gray, 1999; Prince 1999). The population surrounding the site diminished, and new structures were constructed over the buried royal court complex by individuals of lower social status (Iannone 2003, 2005; Iannone et al. 2004). It appears as though long-standing local families who had some degree of influence in the community before Minanha’s rise to prominence returned to their position as community leaders after the dissolution of the royal court (Iannone and Schwake 2010; McCane et al. 2009; Seibert 2006). A small population continued to live in the area into the Early Postclassic (C.E. 900-1200) (Iannone 2005).

4.2 Sample overview

The sample used in this project initially consisted of 30 molars recovered during excavations in the epicentre, site core, and peripheral (Contreras Valley) areas at Minanha. Because most of the teeth were loose, and many burials contained more than one individual, it was not possible to verify that each tooth represented a unique individual. As such, teeth sampled from multiple burial contexts were only retained for this analysis if it was possible to determine that they represented unique individuals. For example, if two maxillary right M1s were sampled from a multiple burial context, these were considered unique and both were retained. In contrast, if a maxillary right M1 and a mandibular left M2 were sampled from a multiple burial
context, it was impossible to verify that these represented two individuals and, as such, only one of the tooth samples was utilized). This approach reduced the sample to 20 specimens (the sample is reviewed in Table 4.2). Specimen preservation ranges from very poor (e.g., partial, brittle, discoloured and cracked) to excellent (e.g., whole [including roots], no discolouration or cracks), although the majority of the sample was quite well preserved (see Table 5.1).

The majority of the sample (n=17/20) was recovered from the epicentre (n=10) and from the 20% stratified random sample of the settlement units (identified as single or grouped mounds [Snetsinger 2012:27]) in the site core zone (n=7); SARP also implemented a 15% stratified random sampling strategy of the known settlements within the Contreras Valley and the remaining three samples are from this area (Iannone 2006; McCane et al. 2009; McCormick 2007, 2008). If the concentric model of status and settlement is accepted (i.e., elites in the epicentre, lower status in the periphery) it would suggest that this sample is biased towards higher status individuals. However, current understandings of Maya settlement (e.g., low density urbanism e.g., Isendahl and Smith 2012) and SARP at Minanha do not support this model of Maya settlement. For example, Group K in the epicentre may have been a domestic space used by lower status individuals serving the royal court (Slim 2005:188-191). In the site core, many non-elite settlements were inhabited by individuals with varying degrees of status (as evidenced by mortuary behaviour [Schwake 2008:184; Snetsinger 2012:33,204]). In the periphery both modest and more complex elaborate settlements (such as MRS4 and MRS15) co-existed and were inhabited during the Late Classic (Snetsinger 2012). In addition to geographical variations in status, the dynamics of status also changed temporally at Minanha. For example, Iannone et al. (2005) suggest that the social prominence of certain long-established families declined in importance during the
period of royal rule at Minanha. However, after the dissolution of the royal court, these families may have risen in social prominence once again.

4.3 Previous research on this sample

A variety of research has already been conducted on the human remains from Minanha. Schwake (1999, 2000, 2001, 2002, 2003, 2008) has examined the burial contexts of excavated interments at Minanha and has made important inferences regarding the social statuses of the individuals interred there (see Schwake 1999, 2000, 2001, 2002, 2003). Snetsinger (2012) further examined mortuary practices at Minanha and, due to another decade’s worth of excavations, was able to explore burial practices at Minanha spatially and temporally. Stronge (2012) examined diet at Minanha using carbon and nitrogen isotope analysis. Thus, the majority (18/20) of the individuals used in this thesis have been previously studied. Two molars (designated Specimens 35 and 36) were an isolated recovery from the floor fill beneath the ball court and therefore have not been studied extensively. Stronge (2012) reported radiocarbon, stable carbon and stable nitrogen isotope data for eight individuals included in this study (see Table 7.1). Twelve individuals (eight with stable carbon and nitrogen isotope data and radiocarbon dates) have been assigned to broad age categories (see Snetsinger 2012:275-276 [Table 51]). In accordance with Welsh’s (1988) burial typology, the following burial contexts were recognised (Snetsinger 2012:82 [Table 4]): offering (n=2); crypt/elaborate (n=4); crypt/simple (n=5); cistern/partial (n=1); simple/simple (n=1); chultun (n=3); unclassified (n=4). Four individuals were not recovered from their original burial contexts (e.g., they were recovered from looters’ back dirt). The individuals in this study represent nearly all periods of occupation at Minanha (Late Preclassic-Early Postclassic), with radiocarbon dates spanning from 100 B.C.E. to C.E. 1260.
Table 4.2. Sample composition and detailed information about each specimen. The asterisk denotes that a specimen date is based on associated ceramics rather than radiocarbon data.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Provenience</th>
<th>Period</th>
<th>2σ14C Dates (calibrated)</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
<th>Tooth Type</th>
<th>Burial Type</th>
<th>Burial Location</th>
<th>Catalogue #</th>
</tr>
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<tbody>
<tr>
<td>3</td>
<td>Structure 5A, Unit 5A-1a, Feature 5A-#/4</td>
<td>Late Preclassic</td>
<td>B.C.E. 100-400</td>
<td>70</td>
<td>M1</td>
<td>offering</td>
<td>epicentre</td>
<td>885</td>
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<tr>
<td>7</td>
<td>Structure 38A, Unit 38A-1; Level 1F</td>
<td>Middle, Late, Terminal Classic</td>
<td>C.E. 870-880</td>
<td>70</td>
<td>M2</td>
<td>elaborate</td>
<td>epicentre</td>
<td>2020</td>
</tr>
<tr>
<td>8</td>
<td>MRS15-M2: Unit MRS15-M2-1a and b - Burial MRS15-M2-8/1</td>
<td>Early, Middle Classic</td>
<td>C.E. 540-650</td>
<td>70</td>
<td>M1</td>
<td>partial clot</td>
<td>sitecore</td>
<td>2474</td>
</tr>
<tr>
<td>10-13v</td>
<td>Structure 77S, Unit 77S-1, Burial 77S-8/2</td>
<td>Early, Middle Classic</td>
<td>C.E. 420-650</td>
<td>70</td>
<td>M1</td>
<td>elaborate</td>
<td>sitecore</td>
<td>2474</td>
</tr>
<tr>
<td>10-13vii</td>
<td>Structure 77S, Unit 77S-1; Burial 77S-8/2</td>
<td>Early, Middle Classic</td>
<td>C.E. 420-650</td>
<td>70</td>
<td>M1</td>
<td>elaborate</td>
<td>sitecore</td>
<td>2474</td>
</tr>
<tr>
<td>10-13viii</td>
<td>Structure 77S, Unit 77S-1; Burial 77S-8/2</td>
<td>Early, Middle Classic</td>
<td>C.E. 420-650</td>
<td>70</td>
<td>M1</td>
<td>elaborate</td>
<td>sitecore</td>
<td>2474</td>
</tr>
<tr>
<td>11i</td>
<td>Structure 77S, Burial 77S/B-1/1*</td>
<td>Middle, Late, Terminal Classic; Early Postclassic</td>
<td>C.E. 650-980</td>
<td>70</td>
<td>M1</td>
<td>simple crypt</td>
<td>sitecore</td>
<td>2213</td>
</tr>
<tr>
<td>11ii</td>
<td>Structure 77S, Burial 77S/B-1/1*</td>
<td>Middle, Late, Terminal Classic; Early Postclassic</td>
<td>C.E. 650-980</td>
<td>70</td>
<td>M1</td>
<td>simple crypt</td>
<td>sitecore</td>
<td>2213</td>
</tr>
<tr>
<td>19</td>
<td>Other Chultume M2, Unit OP113; Burial OP113-B/1 (Individual #2 of 3)</td>
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<td>C.E. 980-1140</td>
<td>70</td>
<td>M2</td>
<td>chutun</td>
<td>epicentre</td>
<td>4151</td>
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<tr>
<td>20</td>
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<td>C.E. 980-1140</td>
<td>70</td>
<td>M2</td>
<td>chutun</td>
<td>epicentre</td>
<td>4151</td>
</tr>
<tr>
<td>21</td>
<td>Structure 5B, Unit 5B-1; Burial 5B-8/2</td>
<td>Early, Middle Classic</td>
<td>C.E. 410-580</td>
<td>70</td>
<td>M1</td>
<td>partial clot</td>
<td>sitecore</td>
<td>3984</td>
</tr>
<tr>
<td>22</td>
<td>Structure 17SAQ; Unit 17SAQ-1a, Burial 17SAQ-8/2</td>
<td>Late, Terminal Classic; Early Postclassic</td>
<td>C.E. 780-980</td>
<td>70</td>
<td>M1</td>
<td>simple grave</td>
<td>sitecore</td>
<td>5056</td>
</tr>
<tr>
<td>28i</td>
<td>MR84-M8; Burial MR84-M8-8/1</td>
<td>Early Postclassic</td>
<td>C.E. 900-1080</td>
<td>70</td>
<td>M1</td>
<td>simple crypt</td>
<td>peripheral</td>
<td>8023</td>
</tr>
<tr>
<td>33</td>
<td>Structure - Other AP; Unit AP-2; Burial AP-8/1 (Individual #1)</td>
<td>Middle Classic</td>
<td>C.E. 600-660</td>
<td>70</td>
<td>M1</td>
<td>simple crypt</td>
<td>peripheral</td>
<td>7776</td>
</tr>
<tr>
<td>34</td>
<td>Structure - Other AP; Unit AP-2; Burial AP-8/1 (Individual #2)</td>
<td>Early Classic</td>
<td>C.E. 400-540</td>
<td>70</td>
<td>M1</td>
<td>simple crypt</td>
<td>peripheral</td>
<td>7776</td>
</tr>
<tr>
<td>35</td>
<td>Structure 2A, Unit 2A-8, Vl 4c</td>
<td>Early Classic</td>
<td>C.E. 250-550*</td>
<td>70</td>
<td>M1</td>
<td>unclassified</td>
<td>epicentre</td>
<td>7812</td>
</tr>
<tr>
<td>36</td>
<td>Structure 2A, Unit 2A-8, Vl 3</td>
<td>Late Classic</td>
<td>C.E. 675-810*</td>
<td>70</td>
<td>M3</td>
<td>unclassified</td>
<td>epicentre</td>
<td>7576</td>
</tr>
<tr>
<td>37</td>
<td>Structure 42K, Unit 42 K-1; Burial 42K-8/1</td>
<td>Early, Late Postclassic</td>
<td>C.E. 1040-1280</td>
<td>70</td>
<td>M1</td>
<td>partial clot</td>
<td>epicentre</td>
<td>2274</td>
</tr>
<tr>
<td>38</td>
<td>Structure MR589-M1; Unit MR589-M1-1a, Feature MR589-M1-F/2</td>
<td>Middle, Late Classic</td>
<td>C.E. 550-810*</td>
<td>70</td>
<td>M2</td>
<td>offering</td>
<td>peripheral</td>
<td>6296</td>
</tr>
</tbody>
</table>
4.4 Summary

The twelve years of excavations at Minanha have provided a wealth of archaeological data used to further the understanding of long-term socioenvironmental dynamics at the site and their effects on organisation and behaviour. They have provided archaeologists with an understanding of Minanha’s history, from its simple beginnings, to the establishment of a royal court, to the dissolution of royal rule a century later, and to the eventual return to a less complex society.

The 20 molars comprising this thesis project’s sample were recovered throughout the twelve years of excavations and represent nearly all periods of occupation at Minanha as well as different social classes. Each individual has been radiocarbon dated (17/20) or has an associated radiocarbon date (3/20); over half of the sample has been aged; and each individual has accompanying burial contextual data (i.e., grave type and grave offerings). The wealth of data provided for each individual allows for a more detailed understanding of site dynamics at Minanha.

The following chapter details the methods utilised to prepare the sample for strontium isotope analysis as well as providing further information on mass spectrometry methods and the accuracy, reproducibility, and correction for mass bias.
Chapter 5: Methods

This chapter details the laboratory, experimental, and analytical and statistical methods used throughout this research project. Sample selection and physical and chemical preparation techniques are discussed first. Following is a brief introduction of the two methods utilised in this study to identify non-local strontium isotope values.

Then, a description of the method used to introduce the prepared samples into the mass spectrometer, the accuracy and reproducibility of the instrument, and the correction for mass bias follows. I will then introduce Fourier-Transform Raman spectroscopy, the method used to assess the integrity of the sample. Lastly, the statistical tests used to analyse the data are discussed.

5.1 Research methods

The dental samples were selected for \(^{87}\text{Sr}/^{86}\text{Sr}\) measurement based on two criteria: 1) they represented only one human individual (reviewed in Chapter 4: 48); 2) if there was more than one tooth per individual, the tooth in the best condition (macroscopically determined) was selected. Prior to selection, all specimens were: identified as either maxillary or mandibular, sided (i.e., left or right) and positioned in the dental arcade (i.e., M\(_1\) vs. M\(_2\)). Twenty teeth representing twenty unique individuals were selected and comprise the sample for this project.

Prior to analysis, all teeth were first ultrasonically cleaned using deionised (DI) water in a Branson 2510 R-MT (117v) Ultra Sonic Cleaner. Each tooth was sonicated in a beaker of DI water for 10 minutes. Water was decanted and replenished after each sonication until the water remained clear; most samples required 3-4 cycles. Once the sample was clean, the specimen was set aside to air dry for 24hrs.

After drying for 24hrs, each tooth was weighed using an Ohaus Adventurer Analytical Balance AR0640 weighing scale; weight was recorded to the 4\(^{th}\) decimal
place (i.e., accuracy = 0.0001g). Subsequently three measurements were taken from each tooth (mesiodistal diameter, buccolingual diameter, and crown height) using digital calipers and the degree of molar surface wear and dental calculus formation were recorded, all following the procedures described in Buikstra and Ubelaker (1994:53-56). In addition, the condition of each tooth was recorded (i.e., completeness, discolouration, presence or absence of carious lesions, cracking, and pitting) and each specimen was photographed from six different perspectives (occlusal, lingual, buccal, distal, mesial, and distal roots). Removing enamel from the specimens was extremely destructive and, in most cases, destroyed the specimens. Therefore, these pictures have been digitally archived should any future research be interested in the initial condition of the specimens.

Sampling commenced after all teeth were cleaned, documented, and photographed. Inorganic materials such as hydroxyapatite are much more resilient to chemical alteration than organic materials (reviewed in Chapter 2); as such, sampling focussed exclusively on dental enamel in molar cusps. For consistency, the mesiolingual cusp was targeted for sampling (see Table 5.1). However, any mesiolingual cusp that exhibited cracks, discolouration, dental pathology, or extensive wear was not sampled (following Wright et al. 2010); in its place, a mesiobuccal cusp was sampled instead. To confirm that there was no difference between $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios obtained from mesiolingual and mesiobuccal cusps on the same tooth, five specimens were sampled twice (mesiolingual and mesiobuccal cusps) (see Table 6.1)

5.2 Identifying non-local $^{87}\text{Sr}/^{86}\text{Sr}$ values

Two methods of identifying non-local individuals have been used in relevant literature and will be defined in this thesis as: 1) the outlier method and 2) the baseline
method (Ezzo et al. 1997; Price et al. 1994). The outlier method utilises the $^{87}\text{Sr}/^{86}\text{Sr}$ values of the sample under study and defines a local range by eliminating outliers. Outliers will be defined in this thesis using two methods: 1) individuals with values greater than two standard deviations from the mean (following Price et al. 1994) and 2) plotting the data and visually identifying the outliers (following Wright 2005a).

The baseline method defines a range of local $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic values by measuring the $^{87}\text{Sr}/^{86}\text{Sr}$ of soil, water, plants, animals, or archaeological specimens. Such baseline $^{87}\text{Sr}/^{86}\text{Sr}$ values for Minanha have not been acquired, however $^{87}\text{Sr}/^{86}\text{Sr}$ values for neighbouring sites have been published (Freiwald 2011; Hodell 2004; Price et al. 2008; Thornton 2011; Yaegar and Freiwald 2009) (see Figure 5.1) and will be used as the baseline data for this thesis. Both the outlier and baseline methods will be utilised in this thesis to ensure that the data is interpreted as broadly and conservatively as possible.

5.3 Laboratory methods

Sampling was conducted under an illuminated 10x magnifying lamp using a Foredom 1/6 HP SR motor drill fitted with a Foredom H 44T handpiece. To remove any contamination from the burial environment, the outer 1-2mm of enamel on the sampled cusp was abraded using a Foredom carbide bur 3.8mm (head diameter 7/32”). Following the abrasion, a portion of cusp enamel was removed using a white carbide bur (FG-170). To prevent cross-contamination, a new carbide bur was used for each sample and the shank holding these burs was thoroughly cleaned with DI water between sampling. Once the enamel pieces were removed, they were examined under a stereoscopic microscope (max. magnification 40x) to ensure that the sample did not contain any organic (i.e., dentin) material. Samples were then weighed using an Ohaus Adventurer Analytical Balance AR0640 weighing scale and weights were
recorded to the 4th decimal place (i.e., 0.0001g). Enamel samples weighed on average 0.023g (see Table 5.1).

To remove adsorbed and pore-filling strontium, sample pretreatment follows the procedure outlined in Thornton (2011:3256). Each enamel sample was placed into sterile 2ml eppendorf tubes and ~1.5ml of 0.1N acetic acid was added using a pipette and allowed to react for 30 minutes. Each eppendorf tube was shaken at five minute intervals during the 30 minute reaction period. After 30 minutes, the solution was

Figure 5.1. Strontium isotope zones of the Yucatán as identified by Hodell et al. (2004) and localised $^{87}\text{Sr}/^{86}\text{Sr}$ values from published studies. Adapted from Thornton (2011:3255).
<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Whole Tooth Preservation</th>
<th>Cusp Sampled</th>
<th>Sample Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Good&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Mesiolingual</td>
<td>0.0175g</td>
</tr>
<tr>
<td>3(duplicate)</td>
<td>Good</td>
<td>Mesio buccal</td>
<td>0.0156g</td>
</tr>
<tr>
<td>7</td>
<td>Poor&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Mesiolingual</td>
<td>0.0202g</td>
</tr>
<tr>
<td>8</td>
<td>Fair&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Mesiolingual</td>
<td>0.0221g</td>
</tr>
<tr>
<td>10-13i</td>
<td>Fair</td>
<td>Mesiolingual</td>
<td>0.0352g</td>
</tr>
<tr>
<td>10-13i(duplicate)</td>
<td>Fair</td>
<td>Mesio buccal</td>
<td>0.0168g</td>
</tr>
<tr>
<td>10-13v</td>
<td>Fair</td>
<td>Mesiolingual</td>
<td>0.0168g</td>
</tr>
<tr>
<td>10-13vii</td>
<td>Poor</td>
<td>Mesiolingual</td>
<td>0.0317g</td>
</tr>
<tr>
<td>10-13viii</td>
<td>Good</td>
<td>Mesiolingual</td>
<td>0.0163g</td>
</tr>
<tr>
<td>11i</td>
<td>Fair</td>
<td>Mesiolingual</td>
<td>0.0369g</td>
</tr>
<tr>
<td>11i(duplicate)</td>
<td>Fair</td>
<td>Mesio buccal</td>
<td>0.0226g</td>
</tr>
<tr>
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<td>Mesiolingual</td>
<td>0.0388g</td>
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<td>0.0193g</td>
</tr>
<tr>
<td>21(duplicate)</td>
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<td>Mesio buccal</td>
<td>0.0279g</td>
</tr>
<tr>
<td>22</td>
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<td>0.0348g</td>
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<td>23iii(duplicate)</td>
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<td>0.0252g</td>
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</tbody>
</table>

<sup>1</sup>Good = tooth whole; little or no cracks or discolouration; enamel strong
<sup>2</sup>Poor = largely discoloured, extensive cracking; dentine exposed; enamel brittle
<sup>3</sup>Fair = some discolouration/cracking; little to no dentine exposure; enamel moderately strong

**Table 5.1.** Enamel condition, cusp sampled, and sample weight of specimens.

decanted using a pipette (the pipette tip was replaced between each sample). Each tube was then filled with 1.5ml of DI water and shaken well. The water was then decanted using a pipette (the pipette tip was replaced between each sample). The samples were air dried in the eppendorf tubes with the lids open for 24hrs.

Once the samples were cleaned and dried they were transported to the Water Quality Centre (Trent University) for isotopic analysis. Dissolution, elution, and subsequent analyses were conducted by Senior ICP-MS research scientist Dr. Bastian
Georg using the protocols established in-house and in Thornton (2011:3256). In a clean room, each enamel sample was transferred to individual refluxed Teflon vials containing 3 ml 3N HNO₃. The vials were capped and placed on a hot plate for 30 minutes at 120°C. Once dissolved, the samples were uncapped and left on the hot plate at 80°C to evaporate to dryness. The dried residuum was redissolved in 1 ml 3N HNO₃ to prepare for insertion into Sr-spec columns. The Sr-spec columns contained ~2 g of Eichrom Sr-spec resin pre-conditioned with 10 ml 3N HNO₃ and [the columns] were prewashed with 20 ml 3N HNO₃ followed by 20 ml 0.05N HNO₃ and finally with 10 ml ultra-pure DI water (18.2 MOhm). The samples were loaded in 1 ml 3N HNO₃ and were washed through with 20 ml 3N HNO₃. The strontium in the samples was recovered in an elution of 9 ml 0.05N HNO₃ that was allowed to evaporate to dryness before being redissolved in 20 μl 15N HNO₃ and then diluted to ~2% HNO₃ with 0.98 ml ultrapure DI water.

5.4 Instrumentation

5.4.1 Trent University

Strontium isotopic measurements were performed using a Thermo-Fisher NEPTUNE-Plus multi collector-inductively coupled plasma mass spectrometer (MC-ICP-MS) in static mode. A standard stable-sample-introduction spray chamber (ESI Inc., Omaha, U.S.) and a self-aspirating microconcentric PFA nebuliser (ESI-Inc., Omaha, U.S.) introduced the sample (~1 ml) into the instrument at a flow rate of 0.1 ml/min. Accuracy was monitored by running the reference standard NIST SRM 987 along with the dissolved enamel samples. Instrumental mass bias was corrected for using a true $^{86}\text{Sr}/^{88}\text{Sr}$ ratio of 0.1194 and an exponential law. The NIST SRM 987 value at the Trent University Water Quality Centre is 0.710236 with an error margin of ± 0.000012 (two standard deviations) and has been measured within this range for
two years. The certified value of NIST SRM 987 is 0.710248 ± 0.000020, placing the Water Quality Centre’s reference standard measurements within the certified value’s error margin.

5.4.2 Memorial University

Because this was the first strontium isotope extraction and analysis of archaeological tooth enamel at the Water Quality Centre, a subset of seven teeth was sent to Memorial University (Dr. Vaughan Grimes) for external validation. Dr. Grimes’ lab has been successfully extracting and analyzing Strontium from archaeological tooth enamel since 2010.

5.5 Sample preservation

For this research, we attempted to develop a novel application of Fourier-Transform spectroscopy to assess the preservation of biogenic strontium. These analyses were conceptualized by and conducted under the guidance of Dr. Andrew Vreugdenhil, Department of Chemistry, Trent University and carried out in his laboratory. FT-Raman spectroscopy operates similarly to FTIR spectroscopy in that it detects the vibrational frequencies of atomic bonds to determine crystalline structure (for a recent review, see Felix-Rivera and Hernandez-Rivera 2012). In addition, and unlike FTIR spectroscopy, it can also identify the inclusion of specific elements such as Sr, Pb, Cd, and F (King et al. 2011). Although spectra were acquired for each specimen, it was impossible to isolate and interpret the spectra associated with strontium. This was due to the lack of information on the expected strontium spectra in a modern, unaltered tooth. Ultimately, due to the unexpected complexity of this method and time constraints, this research was abandoned; however, it has potential as a tool to test diagenesis and as such should continue to be explored.
5.6 Statistical methods

Statistical testing was performed using the free-ware program R. Tests for normality (Shapiro-Wilk Test) and homogeneity of variances (Bartlett’s Test) were utilised to assess the datasets before performing parametric/non-parametric tests. Student’s t-tests, one-way ANOVAs, and Grubb’s tests were used to determine statistically significant differences in the data. Statistical significance was demonstrated by a p value ≤ 0.05.

5.7 Summary

Sample specimens were selected on the basis of preservation and the representation of unique individuals, and sample pretreatment followed established protocols proven to be effective in removing adsorbed, non-biogenic strontium from enamel chunks. Strontium extraction followed protocol established in-house by the Water Quality Centre at Trent University before insertion into the mass spectrometer. The MC-ICP-MS at the Water Quality Centre operates under a reliable and reproducible NIST SRM 987 value that is within the certified reference standard’s error margin. In addition, although we did not use the Raman spectroscopy results to examine the integrity of the samples, it was briefly discussed with a nod to its potential usefulness in bioarchaeology.

The two methods used to identify non-local $^{87}$Sr/$^{86}$Sr values at Minanha, namely, the outlier method and baseline method, as well as the statistical tests used to verify the results of these techniques, are briefly explored and will be further detailed in the following chapter.

The subsequent results chapter presents the MC-ICP-MS data as well as the statistical tests used to analyse the results of the strontium isotope analysis.
Chapter 6: Results

This chapter presents the results of the strontium isotope analysis of 20 enamel samples from Minanha. Statistical tests that validate the accuracy of the Water Quality Centre MC-ICP-MS results, the reproducibility of the MC-ICP-MS results, and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are presented followed by general information relating to the nature of the Minanha $^{87}\text{Sr}/^{86}\text{Sr}$ dataset. Subsequently, two methods used to identify non-local individuals at Minanha are discussed and are followed by an exploration of the spatiotemporal significance of the $^{87}\text{Sr}/^{86}\text{Sr}$ values at Minanha.

6.1 Sample integrity

Stronge (2012) performed Fourier-Transform Infrared spectroscopy on a subset of her sample ($n = 10$) to assess whether bone bioapatite had been altered by diagenesis. Sixty percent ($n = 6$) of the sample subset exhibited crystallinity indices indicative of good bioapatite preservation (e.g., no post-depositional alteration). Given that tooth enamel is considered much more resistant to diagenetic change (reviewed in Chapter 2) it is reasonable to suggest that the tooth enamel at Minanha is well preserved and retains a biogenic isotopic composition.

6.2 Analytical accuracy and precision

The Water Quality Centre MC-ICP-MS has been measuring the NIST SRM 987 standard at 0.710236 with an error margin of $\pm 0.000012$ for two years; this is well within the certified value’s error margin (reference standard NIST SRM 987 = 0.710248 $\pm 0.000020$). During the analysis of this project’s samples, the average measurement of the reference standard was 0.701249. The highest measurement of the standard during the analysis was 0.701264 and the lowest measurement was 0.710232. Although this range was slightly larger than normal for the Water Quality
Centre, these values are still well within the accepted range of the certified value of NIST SRM 987.

Concerning precision, both the Water Quality Centre and Memorial University had standard deviations of $\sigma=0.0004$ for the same seven samples (see Table 6.2). Including all 20 samples, the Water Quality Centre standard deviation was $\sigma=0.0004$.

**6.3 Strontium isotope analysis results**

The $^{87}\text{Sr}/^{86}\text{Sr}$ values for the samples ($n=20$) range from 0.707725‰-0.709113‰, with a mean of 0.708624‰ (see Table 6.1). The median and mode (rounded to the fourth decimal place) are 0.7087‰ and 0.7084‰, respectively. When plotted, the distribution of isotope data approximates a normal distribution ($\sigma=0.0004$); normality is supported by the Shapiro-Wilk test ($W=0.8775, p=0.1462$). A subset of these data ($n=7$) were sent to Memorial University for external validation (see Table 6.2); a paired t-test demonstrates that there are no significant differences between both labs ($t=-1.3112, df=6, p=0.2377$) (see Table 6.1). To test for intra-tooth variability (e.g., mesiolingual vs. mesiobuccal), five specimens were sampled twice (mesiolingual and mesiobuccal cusps) (see Table 6.3). A paired t-test demonstrates that there are no significant intra-tooth differences in isotope ratios ($t=-1.5969, df=4, p=0.9653$). Finally, inter-tooth comparisons demonstrate that tooth position within the dental arcade did not affect $^{87}\text{Sr}/^{86}\text{Sr}$ values ($F=1.9172, df=3, p=0.2249$) (see Table 6.4). Together these data demonstrate that samples from different locations within a tooth and within the dental arcade have comparable isotope values. Publications on strontium isotope analysis in the Maya cultural area typically report their $^{87}\text{Sr}/^{86}\text{Sr}$ values to the fourth decimal place (e.g., Price et al. 2010; Thornton 2011; White et al. 2007; Wright 2005). As such, all $^{87}\text{Sr}/^{86}\text{Sr}$ values will be reported to the fourth decimal place in this paper although statistical tests were run using values to the
<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Water Quality Centre (WQC) $^{87}\text{Sr}^{86}\text{Sr}$ (%)</th>
<th>WQC $^{87}\text{Sr}^{86}\text{Sr}$ Rounded to 4th Decimal Place (%)</th>
<th>Duplicate Samples WQC $^{87}\text{Sr}^{86}\text{Sr}$ (%)</th>
<th>Memorial University $^{87}\text{Sr}^{86}\text{Sr}$ (%)</th>
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Table 6.1. Specimen $^{87}\text{Sr}^{86}\text{Sr}$ values to the 4th and 6th decimal places with Memorial University mass spectrometer results and duplicate sample results.
<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Water Quality Centre $^{87}\text{Sr}/^{86}\text{Sr}$ (‰)</th>
<th>Memorial University $^{87}\text{Sr}/^{86}\text{Sr}$ (‰)</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$ Difference</th>
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Table 6.2. Comparison of Water Quality Centre and Memorial University $^{87}\text{Sr}/^{86}\text{Sr}$ mass spectrometry results.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$ Mesiobuccal (‰) (Duplicate Sample)</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$ Difference</th>
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Table 6.3. Duplicate and intra-tooth $^{87}\text{Sr}/^{86}\text{Sr}$ differences. All these samples were analyzed at the Trent University Water Quality Centre.
<table>
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<th>Specimen</th>
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<th>$^{87}\text{Sr}/^{86}\text{Sr}$ (‰) M2 (n=6)</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$ (‰) M3 (n=1)</th>
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**Table 6.4.** Isotope ratios listed by tooth position. Maxillary and mandibular molars from the same position (e.g., maxillary M1 and mandibular M1) were grouped together (e.g., M1) since molars occupying the same position develop synchronously. All these samples were analyzed at the Trent University Water Quality Centre.
millionth decimal place (as provided by MC-ICP-MS) to improve the accuracy of the statistical results. In addition, to further strengthen the significance tests, tests for normality and homogeneity of variance were conducted beforehand where required.

6.4 Outlier method

Using Price et al.’s (1994) criteria to identify $^{87}\text{Sr}/^{86}\text{Sr}$ outliers (e.g., individuals whose $^{87}\text{Sr}/^{86}\text{Sr}$ values fall more than two standard deviations from the mean), only one individual in the Minanha sample (specimen 37, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7077\%$) is non-local ($z = -2.38$) (see Figure 6.1).

Using Wright’s (2005a) criteria, the most conservative trimming would remove specimens 3 and 37 (see Figure 6.2). This would approximate a local Minanha range of $^{87}\text{Sr}/^{86}\text{Sr} 0.7082-0.7091$. Further trimming of the dataset by removing the lowest data point (specimen 10-13v) and the two highest data points (specimens 21 and 23ii) suggests a local range of $^{87}\text{Sr}/^{86}\text{Sr} 0.7084-0.7090$ (see Figure 6.4). Therefore, using this non-statistical trimming, the local $^{87}\text{Sr}/^{86}\text{Sr}$ range is identified as 0.7084-0.7090; using this criterion, five specimens (3, 10-13v, 21, 23ii, and 37) are identified as non-local.

Statistical analysis of the data offers a more conservative approach to identifying outlying values. Grubbs’ test for outliers identifies specimen 21 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7091\%$) as an outlier ($G=1.2935$, $U=0.9073$, $p=<2.2e^{-16}$) when examining one end of the distribution and specimens 21 and 37 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7077\%$) when examining both ends of the distribution ($G=3.6715$, $U=0.6109$, $p=<2.2e^{-16}$). Specimen 37 may not have been identified as an outlier when examining one end of the distribution due to a masking effect by specimen 3 ($^{87}\text{Sr}/^{86}\text{Sr} 0.7079\%$). Masking effects occur when outliers ‘mask’ or hide the identification of additional outliers by influencing the test statistics. Specimen 3, as the data point furthest away from the
aggregate, is so extreme an outlier that specimens 21 and 37 are not identified as outliers. However, when specimen 3 is removed from the dataset, Grubbs’ test identifies specimens 21 and 37 as outliers (G=2.7085, U=0.5698, p=0.0436) (in addition to specimen 21) for both one and two ends of the distribution. When specimen 37 is removed, Grubb’s test does not identify specimen 3 as an outlier.

Specimen 21 may also exhibit a masking effect – when it is removed from the dataset, specimen 23ii ($^{87}$Sr/$^{86}$Sr = 0.7091‰) is identified as an outlier (G=1.3724, U=0.8895, p=<2.2e-16). When accounting for masking effects, statistical tests identify specimens 21, 23ii, and 37 as outliers, suggesting a local $^{87}$Sr/$^{86}$Sr range of 0.7079-0.7090 (see Table 6.5 and Figure 6.3). $^{87}$Sr/$^{86}$Sr local ranges in Mesoamerica have been reported with a difference between the highest and lowest values as narrow as

![Figure 6.1](image_url)

**Figure 6.1.** Scatterplot of all $^{87}$Sr/$^{86}$Sr values with mean and three standard deviations. This figure represents the application of the Outlier method following Price et al. (1994).
0.0004 (e.g., Price et al. 2010:28) and as broad as 0.0015 (e.g., Wright et al. 2010:172). The ranges suggested by non-statistical trimming and Grubbs’ tests (with differences between the highest and lowest values of 0.0006 and 0.0011, respectively) are consistent with other strontium isotope ranges in Mesoamerica.

6.5 Baseline method

As previously mentioned, baseline $^{87}\text{Sr}/^{86}\text{Sr}$ values have not been acquired at Minanha. Therefore the $^{87}\text{Sr}/^{86}\text{Sr}$ values in this study are compared to published regional $^{87}\text{Sr}/^{86}\text{Sr}$ values and maps of the Yucatán Peninsula (i.e., Freiwald 2011; Hodell et al. 2004; Price et al. 2008; Thornton 2011; Yaegar and Freiwald 2009). Hodell et al. (2004) identified five general strontium isotope regions within the Yucatán Peninsula (see Figure 5.1) using water, rock, soil, and plant samples. Using the data from Hodell et al. (2004), the $^{87}\text{Sr}/^{86}\text{Sr}$ range of Minanha would be expected

![Figure 6.2](image.png)

**Figure 6.2.** Conservative trimming of two lowest $^{87}\text{Sr}/^{86}\text{Sr}$ values. Trimmed dataset in bolded box. This figure represents the conservative application of Wright’s (2005a) outlier method.
Figure 6.3. Outliers identified by statistical tests when the masking effect is taken into account.

Figure 6.4. Liberal trimming with two highest $^{87}\text{Sr}/^{86}\text{Sr}$ values and three lowest $^{87}\text{Sr}/^{86}\text{Sr}$ values removed. Letters a and b (in top right hand corner) denote specimens 23ii and 21 respectively. Trimmed dataset in bolded box. This figure represents a less conservative application of Wright’s (2005a) outlier method.
to fall between ~0.7070-0.7085‰. Only 8/20 Minanha specimens fit within this range (see Figure 6.5), with the mean for the entire sample (0.7086‰) just below the higher end of the range. However, Hodell et al.’s (2004) strontium regions are broadly defined and cannot be expected to account for smaller regional variations in $^{87}\text{Sr} / ^{86}\text{Sr}$.

A localised depiction of $^{87}\text{Sr} / ^{86}\text{Sr}$ zones around Minanha and the Vaca Plateau is shown in Figure 6.6. The $^{87}\text{Sr} / ^{86}\text{Sr}$ range for the Vaca Plateau is identified as ~0.7076-0.7078 (Freiwald 2011; Yaegar and Freiwald 2009) and is expected to be relatively homogeneous throughout the plateau due to the underlying limestone formation (Freiwald 2011). Caracol, 25 km south of Minanha, has an established range of 0.7074-0.7080 (Freiwald 2011; Price et al. 2008, 2010), and Freiwald (2011:89) acquired $^{87}\text{Sr} / ^{86}\text{Sr}$ values in the northern Vaca Plateau of ~0.7078. Using these data, the local range would be 0.7074-0.7080‰, and only two specimens from the Minanha sample (specimen 3 [0.7078‰], specimen 37 [0.7077‰]) fit within this range and would be identified as local.

![Figure 6.5](image)

**Figure 6.5** Minanha $^{87}\text{Sr} / ^{86}\text{Sr}$ values plotted against Hodell et al.’s (2004) range for the Southern Lowlands (dark grey).
The Belize River Valley region (see Figure 6.6), just north of the Vaca Plateau, has a $^{87}\text{Sr}/^{86}\text{Sr}$ range of 0.7082-0.7091‰ (Freiwald 2011:85). The neighbouring site of Xunantunich (at the western edge of this region and <20 km from Minanha) has a $^{87}\text{Sr}/^{86}\text{Sr}$ range of 0.7084-0.7087‰ (Freiwald 2011:134). The Belize River Valley region’s strontium isotope range (0.7082-0.7091‰) is more similar to the $^{87}\text{Sr}/^{86}\text{Sr}$ ranges suggested for Minanha using the outlier method (see Table 14). However, the river valley region is situated above Palaeocene-Eocene limestone, which is younger than the Cretaceous period limestone of the Vaca Plateau, and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are further influenced by sedimentary deposition by the Belize River and the Macal River (Freiwald 2011).
The $^{87}\text{Sr}/^{86}\text{Sr}$ values for the archaeological specimens from Minanha are difficult to interpret. Although Minanha is situated in the Vaca Plateau, the majority (n=18/20) of the specimens exhibit $^{87}\text{Sr}/^{86}\text{Sr}$ values outside the $^{87}\text{Sr}/^{86}\text{Sr}$ range expected for the Vaca Plateau (~0.7076-0.7078‰) (Freiwald 2011; Yaegar and Freiwald 2009). Given this result, it seems unwise to use the $^{87}\text{Sr}/^{86}\text{Sr}$ range for the Vaca Plateau as the local signature for Minanha. In contrast, given the close agreement between the baseline data for the Belize River Valley (0.7082-0.7091‰) and the outlier data from non-statistical trimming of the Minanha dataset (0.7084-0.7090‰), a local range based on the Minanha dataset (e.g., 0.7084-07090‰) seems reasonable. Using this local range, five individuals from Minanha are identified as non-locals (specimens 3, 10-13v, 21, 23ii, and 37) (see Figure 6.7).

**Figure 6.7.** Suggested Minanha $^{87}\text{Sr}/^{86}\text{Sr}$ range in dark grey.
<table>
<thead>
<tr>
<th>Method</th>
<th>87Sr/86Sr Local Range (%o)</th>
<th>Samples identified as non-local using this method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Outlier method</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price et al.’s method (1994)</td>
<td>0.7079-0.7094</td>
<td>37</td>
</tr>
<tr>
<td>Wright’s method (2005a)</td>
<td>0.7082-0.7091</td>
<td>3, 10-13v</td>
</tr>
<tr>
<td>Non-statistical trimming (liberal)</td>
<td>0.7084-0.7090</td>
<td>3, 10-13v, 21, 23ii, and 37</td>
</tr>
<tr>
<td>Statistical trimming (Grubbs’ test)</td>
<td>0.7079-0.7090</td>
<td>21, 23ii, and 37</td>
</tr>
<tr>
<td>2. Baseline method</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yucatán Peninsula (Hodell et al. 2004)</td>
<td>0.7070-0.7085</td>
<td>7, 10-13i, 10-13vii, 10-13viii, 11i, 20, 21, 22, 23ii, 35, 36, 38</td>
</tr>
<tr>
<td>Caracol and Vaca Plateau (Freiwald 2011; Yaegar and Freiwald 2009)</td>
<td>0.7074-0.7080</td>
<td>7, 8, 10-13i, 10-13v, 10-13vii, 10-13viii, 11i, 11iii, 19, 20, 21, 22, 23ii, 33, 34, 35, 36, 38</td>
</tr>
<tr>
<td>Belize River Valley (Freiwald 2011)</td>
<td>0.7082-0.7091</td>
<td>3, 37</td>
</tr>
</tbody>
</table>

**Table 6.5.** A comparison of the range of local 87Sr/86Sr values using both the outlier and baseline methods.

Table 6.5 displays strontium isotope ranges and non-local individuals as identified by the outlier and baseline methods examined in this study as well as by techniques that other researchers have used.

**6.6 Spatiotemporal significance of the data**

Trends within the data relating to distinct temporal periods or of spatial significance were also examined. Specifically, individual 87Sr/86Sr values were tested in the contexts of burial location, grave type, drought periods, and periods of site development.
Stronge (2012:88) found a relationship between δ\textsuperscript{13}C\textsubscript{ap} values and burial location suggesting a difference in diet that might indicate differing social strata. For this study, a One-Way ANOVA test (F=0.5886, df=2, p=0.5861) suggests that there is no significant relationship between an individual’s \(^{87}\text{Sr}/^{86}\text{Sr}\) value and where they were buried (see Figure 6.8). When three specimens representing the peripheral region of Minanha were removed and just the site core (n=7) and epicentre (n=10) were compared, there were no significant differences between burial location and \(^{87}\text{Sr}/^{86}\text{Sr}\) values (t=-0.7028, df=14.053, p=0.4936).

Six different grave types have been identified at Minanha using Welsh’s (1988) typology (Snetsinger 2012:149), five of which are represented by this sample. To determine if grave type and \(^{87}\text{Sr}/^{86}\text{Sr}\) values are related, a One-Way ANOVA test was performed. The “offering”, “partial cist”, “simple grave”, and “unclassified” grave types were underrepresented in this sample and could not be tested statistically.
Figure 6.9. Boxplot of $^{87}$Sr/$^{86}$Sr values grouped by grave type. Partial cist, unclassified, offering, and simple grave omitted.

One-Way ANOVA results ($F=0.1618$, df=2, $p=0.8549$) suggest that there is no significance difference between burial type and $^{87}$Sr/$^{86}$Sr values from specimens interred in elaborate crypts, simple crypts, and chultun chambers (see Figure 6.9). Chronological differences in $^{87}$Sr/$^{86}$Sr values were tested; two periods [Late to Terminal Preclassic (400 B.C.E.-C.E. 250) and the Late Postclassic (C.E. 1200-1525)] were omitted due to small sample sizes. There were no significant chronological differences in $^{87}$Sr/$^{86}$Sr values ($F=0.8282$, df=4, $p=0.5287$) (see Figure 6.10). In addition, there were no significance differences in $^{87}$Sr/$^{86}$Sr values among drought periods ($F=0.7888$, df=3, $p=0.5183$) (see Figure 6.11).
Figure 6.10. $^{87}\text{Sr}/^{86}\text{Sr}$ values grouped according to Maya chronology. Terminal Preclassic and Late Postclassic periods omitted due to small sample size.

Figure 6.11. $^{87}\text{Sr}/^{86}\text{Sr}$ values grouped in recorded drought periods and normal conditions. Drought Period One omitted due to small sample size.

6.7 Summary

Analyses indicate that methods of data collection and the data analysis are valid. The strontium in the samples does not appear to have undergone isotopic exchange and therefore preservation of biogenic isotope values seems likely. Two methods were compared for determining the local strontium values, and it was
determined that the non-statistical trimming method was the most acceptable. Statistical comparisons across time and space were difficult and demonstrated that no significant differences in strontium isotope ratios over any of these parameters could be determined.

The following chapter will discuss the results in the context of Maya archaeology.
Chapter 7: Discussion and Conclusions

This chapter discusses the results of the analysis in the context of Maya archaeology. Of a sample size of 20, and using the local range established using the baseline and outlier methods (e.g., non-statistical outlier method), five individuals were identified as non-locals. More conservative methods (e.g., conservative outlier method and Vaca Plateau baseline data) identify 2-3 individuals as non-locals (see Chapter 6). It is impossible to estimate the percentage of the population that was non-local to Minanha at any given time because: 1) all individuals buried at Minanha were not sampled for strontium isotope analysis; 2) the sample that was analysed is very small; and 3) the 20 individuals sampled were buried at different time periods. Out of the total sample of 20 individuals, five were identified as non-local (25%); this percentage drops to 10% using the more conservative methods. Other studies investigating mobility among the Maya using strontium isotope analysis have reported similar percentages of non-locals (see Table 7.1). As such, our results seem to fit the broader pattern.

7.1 Sample viability and comparison to other Mesoamerican samples

The resistance of enamel to diagenetic change (Hoppe et al. 2003; Legeros 1981) (reviewed in Chapter 2) and the relative ease of removing adsorbed and pore-filling diagenetic strontium have given researchers confidence in the validity of their $^{87}\text{Sr}/^{86}\text{Sr}$ values without performing diagenesis testing (Price et al. 2000, Price et al. 2010; Thornton 2011; White et al. 2007; Wright 2005a,b; Yaegar and Freiwald 2009). This, coupled with the moderate bone bioapatite preservation demonstrated by Stronge (2012) supports the use of tooth enamel from Minanha for strontium isotope analysis and the investigation of human mobility.
Sample sizes, in particular the number of unique individuals analysed, vary in Mesoamerican strontium isotope studies. Some studies, focused on just a few important burials, had sample sizes of less than 10 individuals (e.g., Price et al. 2007, 2008, 2010; Wright 2005b); mid-sized samples averaged between 20-45 individuals (White et al. 2007; Wright et al. 2010; Yaegar and Freiwald 2009 [faunal samples]); and large samples featured >80 unique individuals (Freiwald 2011; Thornton 2011 [faunal samples]; Wright 2005a). This thesis project sits in the mid-size range with 20 unique individuals comprising the sample. Many of these researchers identified between 10-30% of their population as non-local (see Table 7.1). The

<table>
<thead>
<tr>
<th>Reference</th>
<th>Sample Size</th>
<th>% Non-Local Individuals</th>
<th>$^{87}$Sr/$^{86}$Sr Range</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sutinen 2013</td>
<td>20 individuals</td>
<td>~10-25%</td>
<td>0.7077-0.7091</td>
<td>Minanha</td>
</tr>
<tr>
<td>Freiwald 2011</td>
<td>155 individuals</td>
<td>23%&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Varies per Site (see Table 7.2)</td>
<td>Belize River Valley</td>
</tr>
<tr>
<td>Price et al. 2010</td>
<td>10 individuals</td>
<td>30%&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.70604-0.70810</td>
<td>Copán</td>
</tr>
<tr>
<td>Price et al. 2010</td>
<td>9 individuals</td>
<td>44%&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.70630-0.70908</td>
<td>Copán</td>
</tr>
<tr>
<td>Wright et al. 2005a</td>
<td>83 individuals</td>
<td>~12-21%</td>
<td>0.70406-0.71626</td>
<td>Tikál</td>
</tr>
<tr>
<td>Wright et al. 2010</td>
<td>27 individuals</td>
<td>~22%&lt;sup&gt;4&lt;/sup&gt;</td>
<td>0.70419-0.71050</td>
<td>Kaminaljuyu</td>
</tr>
</tbody>
</table>

<sup>1</sup> Percentage represents an average calculated from the incidence of non-locals at 15 sites.

<sup>2</sup> This sample is comprised of commoners from Copán.

<sup>3</sup> This sample is from the Copán acropolis only.

<sup>4</sup> Only strontium data were included here; this study also examined $\delta^{18}$O.

**Table 7.1.** Comparisons of Mesoamerican studies on population mobility. Faunal studies were not included.
<table>
<thead>
<tr>
<th>Site</th>
<th>Lower Range</th>
<th>Upper Range</th>
<th>Number of Individuals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xunantunich</td>
<td>0.70794</td>
<td>0.71111</td>
<td>19</td>
</tr>
<tr>
<td>San Lorenzo</td>
<td>0.70812</td>
<td>0.70938</td>
<td>2</td>
</tr>
<tr>
<td>Chaa Creek</td>
<td>0.70841</td>
<td>0.71100</td>
<td>12</td>
</tr>
<tr>
<td>Buenavista</td>
<td>0.70777</td>
<td>0.70971</td>
<td>9</td>
</tr>
<tr>
<td>Cahal Pech</td>
<td>0.70831</td>
<td>0.70942</td>
<td>20</td>
</tr>
<tr>
<td>Zubin</td>
<td>0.70839</td>
<td>0.70987</td>
<td>9</td>
</tr>
<tr>
<td>Esperanza</td>
<td>0.70796</td>
<td>0.70933</td>
<td>3</td>
</tr>
<tr>
<td>Baking Pot</td>
<td>0.70729</td>
<td>0.70955</td>
<td>28</td>
</tr>
<tr>
<td>Floral Park</td>
<td>0.70847</td>
<td>0.71029</td>
<td>3</td>
</tr>
<tr>
<td>Barton Ramie</td>
<td>0.70765</td>
<td>0.70959</td>
<td>28</td>
</tr>
<tr>
<td>Blackman Eddy</td>
<td>0.70848</td>
<td>0.70861</td>
<td>3</td>
</tr>
<tr>
<td>Pook’s Hill</td>
<td>0.70813</td>
<td>0.70893</td>
<td>9</td>
</tr>
<tr>
<td>Saturday Creek</td>
<td>0.70840</td>
<td>0.70927</td>
<td>8</td>
</tr>
<tr>
<td>Franz Harbor</td>
<td>0.70824</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Chapat Caves</td>
<td>0.70816</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7.2. Freiwald’s (2011:133-234) Belize River Valley $^{87}\text{Sr}/^{86}\text{Sr}$ data.

range in enamel $^{87}\text{Sr}/^{86}\text{Sr}$ values is similar among Minanha, Copán (Price et al. 2010), and the majority of the sites in the Belize River Valley (Freiwald 2011). The upper and lower values of these ranges typically differ between 0.002-0.003‰ (Table 7.2). The large ranges found at Tikál and Kaminaljuyu (~0.06‰) are unique relative to most sites [with the exception of a few sites in the Belize River Valley (i.e., Xunantunich, Chaa Creek, and Floral Park)] (Wright 2005a, Wright et al. 2010). However, regardless of the magnitude of differences between the upper and lower values among sites, most $^{87}\text{Sr}/^{86}\text{Sr}$ values fall within 2σ of the sample mean (Freiwald
2011; Price et al. 2010; Wright 2005a; Wright et al. 2010). This suggests that the majority of the individuals from a site share similar strontium isotope values and that any outliers typically are not radical enough to significantly skew the overall distribution.

Minanha and many of the Belize River Valley sites have similarly-sized $^{87}$Sr/$^{86}$Sr ranges because population movement amongst the Maya occurred commonly between neighbouring areas (Freiwald 2011), and Minanha and the Belize River Valley are situated in a region where strontium isotope values are not wildly divergent from one another (see Figure 6.5). The much larger $^{87}$Sr/$^{86}$Sr range at Tikál is likely due to the fact that it was a major centre and would have attracted individuals from further afield. As a medium-sized major centre, Minanha likely did not attract the same types of non-locals as Tikál.

7.2 Factors affecting viable $^{87}$Sr/$^{86}$Sr values

Enamel biogenic $^{87}$Sr/$^{86}$Sr values are relatively robust and are not easily contaminated by diagenetic strontium (Hoppe et al. 2003; Legeros 1981) (see Chapter 2). However, researchers must contend with the fact that although a $^{87}$Sr/$^{86}$Sr value might be purely biogenic in nature, there are other factors that can affect the strontium composition of tooth enamel and confound the identification of non-locals. $^{87}$Sr/$^{86}$Sr values can be affected by a variety of factors not related exclusively to human mobility including: 1) consuming imported food items; 2) consuming water from cenotes or non-local water sources; 3) and consuming foodstuffs from the ocean. Any one of these can impact $^{87}$Sr/$^{86}$Sr values in a way that confounds interpretations about human mobility.

There was a known exchange network at Minanha (McMurdo and Primrose 1999; Stanchly et al. 2008), and if food was being imported for consumption, it could
have affected $^{87}\text{Sr}/^{86}\text{Sr}$ values. Carbon and nitrogen isotope analyses (see Table 7.3) suggest that the diet at Minanha was a composed of resources that could be cultivated or obtained locally. The diet contained a mixture of C$_3$ (beans, tubers, wild terrestrial animals) and C$_4$ (maize and maize-fed animals) resources (with a greater reliance on the latter) in addition to lower-level herbivores (Stronge 2012). The combination of terrestrial plants and lower-level herbivores that made up the diet as indicated by nitrogen isotope analysis could have been grown or acquired locally at Minanha (Stronge 2012). However, Thornton (2011:3261) demonstrated that although a resource could be acquired locally (e.g., deer) it was sometimes exchanged from distances ~25 km to >50 km. If locally available foods were being supplemented by imported foods at Minanha it is possible that the $^{87}\text{Sr}/^{86}\text{Sr}$ composition of individuals was affected. However, it seems doubtful that the majority of food consumed would have been imported in this manner; thus it seems reasonable to infer that strontium isotope ratios were not dramatically altered by this practice.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Stronge ID (2012)</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$ (‰)</th>
<th>$\delta^{13}\text{C}_{\text{col}}$ (‰)</th>
<th>$\delta^{15}\text{N}$ (‰)</th>
<th>$\delta^{13}\text{C}_{\text{ap}}$ (‰)</th>
<th>$\Delta^{13}\text{C}_{\text{ap-co}}$ (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>SS3</td>
<td>0.7079</td>
<td>-13.5</td>
<td>10.7</td>
<td>-5.3</td>
<td>8.2</td>
</tr>
<tr>
<td>7</td>
<td>SS7</td>
<td>0.7088</td>
<td>-9.0</td>
<td>9.2</td>
<td>-3.8</td>
<td>5.2</td>
</tr>
<tr>
<td>8</td>
<td>SS8</td>
<td>0.7084</td>
<td>N/A</td>
<td>N/A</td>
<td>-7.2</td>
<td>N/A</td>
</tr>
<tr>
<td>19</td>
<td>SS19</td>
<td>0.7084</td>
<td>-10.5</td>
<td>9.2</td>
<td>-5.3</td>
<td>5.2</td>
</tr>
<tr>
<td>20</td>
<td>SS20</td>
<td>0.7088</td>
<td>-12.6</td>
<td>9.5</td>
<td>-6.5</td>
<td>6.1</td>
</tr>
<tr>
<td>21</td>
<td>SS21</td>
<td>0.7091</td>
<td>-9.8</td>
<td>9.3</td>
<td>-6.2</td>
<td>3.6</td>
</tr>
<tr>
<td>22</td>
<td>SS22</td>
<td>0.7089</td>
<td>-10.1</td>
<td>9.7</td>
<td>-6.3</td>
<td>3.7</td>
</tr>
<tr>
<td>34</td>
<td>SS34</td>
<td>0.7084</td>
<td>N/A</td>
<td>N/A</td>
<td>-5.1</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 7.3. Stable carbon and nitrogen isotope values of specimens in this study analysed by Stronge (2012:83-84). Italics indicate individuals identified as non-locals.
Sea salt, which can also alter $^{87}$Sr/$^{86}$Sr values, may also have been traded. With a $^{87}$Sr/$^{86}$Sr value of 0.7092, it would raise enamel ratios lower than 0.7092 and lower ratios higher than 0.7092 (Wright 2005a). There is no evidence suggesting that sea salt was imported to Minanha, although a small amount of marine fish and decapods were recovered in some elite contexts (Stronge 2012). Marine animals would carry the same $^{87}$Sr/$^{86}$Sr value as the ocean, therefore increasing the enamel $^{87}$Sr/$^{86}$Sr of inhabitants at Minanha. However, nitrogen isotope data suggests that marine foods were not a substantial component of the diet (Stronge 2012). As such, if sea salt or marine animals were imported, they were likely consumed in such small quantities that it would not dramatically alter the $^{87}$Sr/$^{86}$Sr ratios.

Another important consideration is the consumption of jute snails. A substantial amount of jute snails originating from the Macal River (~5 km to the east) were uncovered at Minanha (Solis 2011). The Macal River (0.7099) has higher baseline $^{87}$Sr/$^{86}$Sr values than are expected in the Vaca Plateau (0.7076-0.7078 [Freiwald 2011; Yaegar and Freiwald 2009]). Jute shells are often ground up and used as an important component in the processing of maize (Solis 2011). If individuals at Minanha were consuming large amounts of jute it is possible that this could have increased the $^{87}$Sr/$^{86}$Sr values of enamel. Stable carbon isotope data (Stronge 2012) would suggest that jute was not a significant portion of the diet at Minanha. Jute meat falls within the range of C3 resources (~33% to ~25% [White et al. 2001:Figure 3]), whereas the stable carbon isotope data from Minanha is more consistent with a mixed diet relying heavily on C4 resources (Stronge 2012). However, given the reliance on maize and the fact that the $^{87}$Sr/$^{86}$Sr ratios for all the non-locals are higher than the range for the Vaca Plateau, it is possible that the use of jute snails for maize preparation may have affected $^{87}$Sr/$^{86}$Sr ratios.
7.3 Non-local individuals at Minanha

The results chapter presented two different methods of identifying non-local individuals: 1) outlier and 2) baseline. The outlier method generated two strontium isotope ranges for Minanha: 0.7079-0.7090 (statistical trimming) and 0.7084-0.7090 (non-statistical trimming) (see Table 7.4). Non-statistical trimming identified five non-locals and statistical trimming identified two non-locals. The baseline method generated a variety of non-local ranges using regional $^{87}\text{Sr}/^{86}\text{Sr}$ maps. After comparing these methods, it was determined that the range established using the non-statistical trimming of the Minanha dataset was the most appropriate. Using this range, specimens 3, 10-13v, 21, 23ii, and 37 were identified as non-locals. Although this author recognises that baseline $^{87}\text{Sr}/^{86}\text{Sr}$ values from modern fauna at Minanha are the strongest method by which to identify a $^{87}\text{Sr}/^{86}\text{Sr}$ range for Minanha, these data are not available at this time. Contextual data is available for many individuals recovered at Minanha. As such, each identified non-local will be discussed in greater detail and potential origins suggested by $^{87}\text{Sr}/^{86}\text{Sr}$ ratios will be examined.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Non-statistical Trimming 0.7084-0.7090</th>
<th>Statistical Trimming 0.7079-0.7090</th>
<th>Caracol 0.7074-0.7080</th>
<th>Belize River Valley 0.7082-0.7091</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.7079</td>
<td>X</td>
<td>X</td>
<td>0.7079</td>
</tr>
<tr>
<td>10-13v</td>
<td>0.7083</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.7091</td>
<td>0.7091</td>
<td>0.7091</td>
<td>X</td>
</tr>
<tr>
<td>23ii</td>
<td>0.7091</td>
<td>0.7091</td>
<td>0.7091</td>
<td>X</td>
</tr>
<tr>
<td>37</td>
<td>0.7077</td>
<td>0.7077</td>
<td>X</td>
<td>0.7077</td>
</tr>
</tbody>
</table>

Table 7.4. Individuals identified as non-locals pertaining to the trimming methods described in the text. ‘X’ denotes that the specimen was not identified as an outlier. NST(non-statistical trimming); ST(statistical trimming); Caracol values (Price 2008) were used to represent the Vaca Plateau to widen the acceptable $^{87}\text{Sr}/^{86}\text{Sr}$ range.
7.3.1 Specimen 3 (Feature 3A-F/4)

This adult individual was interred during the Terminal Preclassic in Structure 3A, the central pyramidal structure of the epicentral eastern shrine complex (Schwake 2008). Represented by cranial, upper thoracic, and long bones, and covered by an inverted ceramic dish, it is likely that this was a secondary burial dedicated to the construction of the Level 5 floor (Schwake 2008). Two Late Classic burials deposited directly above this individual suggest an attempt by the new royal court to link these burials with the older Terminal Preclassic one, thereby strengthening their legitimacy by associating with the ‘traditions and long-term social memory of the Minanha community’ (Schwake 2008:319). This individual’s $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7079 falls outside the local range for Minanha and the range for the Belize River Valley. However, this individual’s $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is one of two that fits within the regional ranges for the Vaca Plateau (Freiwald 2011; Yaegar and Freiwald 2009), and similar $^{87}\text{Sr}/^{86}\text{Sr}$ values have also been reported in the Central Petén region of Guatemala (Thornton 2011) and the Metamorphic province (a stretch of land between the Volcanic Highlands and the Southern Lowlands [see Figure 5.1] ) (Hodell et al. 2004).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Burial Location</th>
<th>Grave Type</th>
<th>Period</th>
<th>Age</th>
<th>Grave Offerings</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Epicentre</td>
<td>Dedicatory Offering</td>
<td>Late Preclassic</td>
<td>18-30 years</td>
<td>Yes</td>
</tr>
<tr>
<td>10-13v</td>
<td>Site Core</td>
<td>Elaborate Crypt</td>
<td>Early-Middle Classic</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>21</td>
<td>Epicentre</td>
<td>Partial Cist</td>
<td>Early-Middle Classic</td>
<td>18-30 years</td>
<td>Yes</td>
</tr>
<tr>
<td>23ii</td>
<td>Periphery</td>
<td>Simple Crypt</td>
<td>Early Postclassic</td>
<td>Adult</td>
<td>Yes</td>
</tr>
<tr>
<td>37</td>
<td>Epicentre</td>
<td>Partial Cist</td>
<td>Early-Late Postclassic</td>
<td>Adult</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 7.5. Contextual information of non-local individuals identified in this study.
Unfortunately, the ceramic dish could not help identify the region where this individual was from. Its style, Sierra Red: Society Hall, was common throughout the Preclassic period (Bond-Freeman 2007).

7.3.2 Specimen 10-13v (Burial 77S-B/2)

The first maxillary molar for this individual was recovered in a Classic period elaborate crypt in the site core beneath 77S, a pyramidal structure of Group S, one of the largest non-elite residential platforms at Minanha (Schwake 2008). Similar to Structure 3A, Structure 77S was the central structure of the Group S eastern shrine complex (Snetsinger 2012). The remains of at least 15 individuals, both female and male, were uncovered within the crypt along with multiple grave offerings that suggested the individuals were of high social status (Schwake 2008). Due to the degree of disarticulation and mixing, it is not possible to identify which individual specimen 10-13v represents. Four first maxillary molars, each representing a unique individual, were sampled from this burial (see Table 7.6). This specimen represents the only non-local individual. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for this individual falls outside the local range for Minanha (and also outside the range for Caracol and the Vaca Plateau) but it does fall within the range for the Belize River Valley. Generally, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios decrease from the north to the south in the Yucatán Peninsula (Freiwald 2011); therefore, this individual’s $^{87}\text{Sr}/^{86}\text{Sr}$ ratio would fall within range of the neighbouring site of Xunantunich and sites north of Minanha (e.g., Colha and Lamanai) (see Figure 5.1). This individual’s $^{87}\text{Sr}/^{86}\text{Sr}$ value also falls within the range of the Metamorphic province (see Figure 5.1).

Some of the grave offerings in this burial may have held ties to other Maya sites. For example, the miniature ink containers recovered from this burial have also been found at Copán, El Ceren, Uaxactun, and Aguateca (Reents-Budet 1994:68;
<table>
<thead>
<tr>
<th>Specimen</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-13i</td>
<td>0.7089</td>
</tr>
<tr>
<td>10-13v</td>
<td><strong>0.7083</strong></td>
</tr>
<tr>
<td>10-13vii</td>
<td>0.7087</td>
</tr>
<tr>
<td>10-13viii</td>
<td>0.7086</td>
</tr>
</tbody>
</table>

**Table 7.6.** $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of four specimens from burial 77S-B/2.

Schwake 2008), and a Zacatel Cream-polychrome variety vessel also recovered potentially originated in the Northern Peten Lowlands of Guatemala (Schwake 2008). However, none of these sites exhibit $^{87}\text{Sr}/^{86}\text{Sr}$ values that coincide with specimen 10-13v.

### 7.3.3 Specimen 21 (Burial 53S-B/2)

This individual was interred in the Early-Middle Classic period beneath the courtyard of the terminus building of the causeway originating in the epicentre and passing west of the acropolis (Zehrt and Iannone 2005:64). This individual is one of six individuals discovered at Minanha exhibiting dental modification (Type B5, upper maxillary incisors) and was discovered in a partial cist grave in an extended prone position with an inverted Early Classic bowl over the neck, with arms crossed and hands beneath the pelvis (see Figure 7.1). The legs may have been crossed at the ankles. Zehrt and Iannone (2005:65-67) suggest that the odd positioning of this individual may indicate that they had been bound and interred beneath the courtyard of Structure 53 as a sacrificial offering – a quartz crystal was also discovered within the interment (Snetsinger 2012).

Of the six individuals that exhibited dental modification, four, including specimen 21, were part of the sample for this analysis (specimens 7, 8, 19, and 21).
Table 7.7. $^{87}$Sr/$^{86}$Sr data and contextual information for individuals displaying dental modification.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Dental Modification Type</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
<th>Time Period</th>
<th>Burial Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>E1</td>
<td>0.7088</td>
<td>Middle, Late, Terminal Classic</td>
<td>Epicentre</td>
</tr>
<tr>
<td>8</td>
<td>B4</td>
<td>0.7084</td>
<td>Early, Middle Classic</td>
<td>Periphery</td>
</tr>
<tr>
<td>19</td>
<td>E1/B4</td>
<td>0.7084</td>
<td>Terminal Classic, Early Postclassic</td>
<td>Epicentre</td>
</tr>
<tr>
<td>21</td>
<td>B5</td>
<td>0.7091</td>
<td>Early, Middle Classic</td>
<td>Epicentre</td>
</tr>
</tbody>
</table>

Table 7.7 displays the individuals in this sample exhibiting dental modification.

Although only a small number of individuals exhibiting dental modification are included in this analysis, it is interesting to note that the non-local individual (specimen 21) had a type of dental modification that was different from the others. Dental modification type B5 has been reported from sites in Guatemala, Belize, and the Southeastern Peten from time periods ranging from the Late Preclassic to the Postclassic (see Table 3 in Williams and White 2005). However, this individual’s $^{87}$Sr/$^{86}$Sr value is too high for sites in these regions, which may indicate that this individual moved after childhood and had dental modification done in the style of a new location. Unfortunately, the small sample size precludes any statistical testing on the individuals with modified teeth. This individual’s (specimen 21) $^{87}$Sr/$^{86}$Sr value (0.7091) falls outside the local Minanha and Vaca Plateau range; however, it falls within the range for the Belize River Valley. $^{87}$Sr/$^{86}$Sr values in the range of ~0.7090 have also been reported for the Northern Lowlands of the Yucatán (e.g., Dzibilchaltun [Thornton 2011]), to the east of Minanha in the Maya Mountains region (Hodell et al. 2004), and in the Metamorphic province (Hodell et al. 2004).
The sacrifice of human victims and their subsequent interment for ritual purposes was a common phenomenon throughout Mesoamerica and occurred for different reasons (Price et al. 2007). Individuals were sacrificed to protect the authority of the state (White et al. 2007), to accompany others in death (Price et al. 2007), or to commemorate phases of construction (Price et al. 2007). The individual interred beneath the courtyard of Structure 53 may have been sacrificed for the latter reason (Zehrt and Iannone 2005:65-67). Non-local sacrificial victims have been identified by strontium and oxygen isotope analysis at Teotihuacán, in central Mexico (White et al. 2007). Both high- and low-status individuals who were not originally from Teotihuacán were sacrificed as dedications to new construction phases or sacrificed to symbolically protect the state (White et al. 2007). Some individuals exhibit $^{87}\text{Sr}/^{86}\text{Sr}$ values that originate in areas neighbouring Teotihuacán and others yielded ratios that indicated an origin in a more remote area (White et al. 2007). Similarly to the individual buried beneath the courtyard of Structure 53, many of these
Table 7.8. Contreras Valley specimens included in this study. Sample 23ii is the only individual whose $^{87}\text{Sr}/^{86}\text{Sr}$ value falls outside the local range.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.7084</td>
</tr>
<tr>
<td>23ii</td>
<td>0.7091</td>
</tr>
<tr>
<td>38</td>
<td>0.7090</td>
</tr>
</tbody>
</table>

individuals were bound and interred with grave offerings (White et al. 2007). The $^{87}\text{Sr}/^{86}\text{Sr}$ value of specimen 21 is consistent with the strontium isotope ratios of areas within the Belize River Valley, the northern Yucatán, and the Maya Mountains. As such, it is not possible to identify the origins of this individual at this time.

7.3.4 Specimen 23ii (Burial MRS4-M3-B/1)

This individual is the only Contreras Valley specimen identified as a non-local individual in this sample. Two individuals were interred in this simple crypt within the eastern shrine complex of the large residential group MRS4-M3 and both are represented by cranial and post-cranial elements. One individual was interred in a seated position. This Early Postclassic grave was intrusive to the terminal plaza floor which was constructed during the Early Classic (Snetsinger 2012). Discovered in the grave with the two individuals were a quartz crystal, shell adornos, and an obsidian chipped stone blade (Snetsinger 2012). Only one of the two individuals was sampled for this project. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for this individual (0.7091) falls outside the local Minanha and the Vaca Plateau ranges; however, it falls within the upper end of the range for the Belize River Valley. Similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratios have also been recorded in the Maya Mountains, the Metamorphic province, or in the Northern Lowlands of the Yucatán (Hodell et al. 2004; Thornton 2011). Two other individuals were sampled
from the Contreras Valley but both have $^{87}\text{Sr}/^{86}\text{Sr}$ values that fall within the Minanha range (see Table 7.8).

**7.3.5 Specimen 37 (Burial 42K-B/1)**

This individual was interred during the Postclassic in a partial cist in Minanha’s epicentre after the infilling of Group J (Slim 2005: Chapter 2). This individual was interred in an extended supine position and is represented by cranial and post-cranial elements. This grave made use of an already-constructed wall to form the western wall of the partial cist and to separate it from a cache (42K-F/1) on the other side (Snetsinger 2012). Although no grave offerings were associated with this burial, this individual is only one of three uncovered at Minanha that exhibits cranial modification (Snetsinger 2012). The individual represented by Specimen 20 also exhibits cranial modification but has a $^{87}\text{Sr}/^{86}\text{Sr}$ value that falls within the Minanha range. The $^{87}\text{Sr}/^{86}\text{Sr}$ value (0.7077) of Specimen 37 is outside the Minanha and Belize River Valley range but it does fit within the expected range for the Vaca Plateau, and similar $^{87}\text{Sr}/^{86}\text{Sr}$ values have also been recorded for the Central Petén region of Guatemala (see Figure 5.1). In addition, this specimen’s $^{87}\text{Sr}/^{86}\text{Sr}$ value fits within the strontium isotope range of the Metamorphic province.

**7.3.6 Characteristics of the non-local individuals at Minanha**

The five non-local individuals cannot be associated with a particular time period, habitation zone, or social position (inferred from grave type/offerings). With the possible exception of one individual (10-13v- age unknown), all were adults at the time of interment. All individuals, except specimen 37, were interred with grave offerings. Table 7.9 displays the possible origins of the non-local individuals. The individuals represented by Specimens 3, 10-13v, and 37 might have originated from a neighbouring region not far from Minanha. In addition, the $^{87}\text{Sr}/^{86}\text{Sr}$ values of
Specimens 21 and 23ii suggest that they might have also originated from the neighbouring Belize River Valley or the Maya Mountains but their strontium isotope values are also consistent with those from the northern Yucatán. An origin in the northern Yucatán would be the most distant origin identified thus far at Minanha. Although mobility amongst the Maya appears to occur locally and across neighbouring regions, long-distance movement is occasionally identified (Freiwald 2011:353; Wright 2005). In addition, each non-local $^{87}$Sr/$^{86}$Sr value at Minanha is consistent with values from the southern Metamorphic province (0.7041-0.7202). It is possible that some of the individuals might have origins in this region; however, as their $^{87}$Sr/$^{86}$Sr values also match neighbouring areas, it is more probable that they originated from closer locations. Freiwald (2011), investigating movement in the Belize River Valley, found that the majority of the non-local individuals in the sample had $^{87}$Sr/$^{86}$Sr values that fit within the ranges of neighbouring locales.

The possible sacrificial victim (specimen 21) shares an identical $^{87}$Sr/$^{86}$Sr value with the individual represented by specimen 23ii. However, the similarities end there – they lived during different time periods and were interred in quite different manners (see following section). In addition, identical $^{87}$Sr/$^{86}$Sr values do not mean identical

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
<th>Possible $^{87}$Sr/$^{86}$Sr Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.7079</td>
<td>Vaca Plateau; Central Petén; Metamorphic province</td>
</tr>
<tr>
<td>10-13v</td>
<td>0.7083</td>
<td>Belize River Valley; north of Minanha (e.g., Xunantúnich); Metamorphic province</td>
</tr>
<tr>
<td>21</td>
<td>0.7091</td>
<td>Belize River Valley; Northern Lowlands of the Yucatán; Maya Mountains; Metamorphic province</td>
</tr>
<tr>
<td>23ii</td>
<td>0.7091</td>
<td>Belize River Valley; Northern Lowlands of the Yucatán; Maya Mountains; Metamorphic province</td>
</tr>
<tr>
<td>37</td>
<td>0.7077</td>
<td>Vaca Plateau; Central Petén; Metamorphic province</td>
</tr>
</tbody>
</table>

*Table 7.9. Specimen $^{87}$Sr/$^{86}$Sr values and possible origins.*
origins; a few areas throughout the Yucatán Peninsula have $^{87}\text{Sr}/^{86}\text{Sr}$ ranges that overlap (e.g., Aguateca, Dos Pilas, Caracol, Cancuen, and Copán).

Freiwald (2011) found relationships between strontium isotope values and burial orientation, skeletal completeness, and number of individuals/burial. Many non-local individuals were oriented in a direction other than south, were represented only by cranial remains, and were part of multiple interments (Freiwald 2011). For the Minanha dataset, group sizes are too small for statistical analysis; however, the relationships that Freiwald (2011) suggested do not appear to be present at Minanha (see Table 7.9). Most non-locals were represented by both cranial and post-cranial remains, were oriented in a variety of directions, and were part of both single and multiple interments. The small sample size at Minanha precludes the identification of potential intimations of non-local individuals.

7.4 Mobility during periods of drought and through time

Palaeoclimatic research conducted not far from Minanha has identified several periods of drought that occurred during the Maya era and that would have affected the Vaca Plateau (Webster et al. 2007). Periods of drought, and the Maya reaction to them, are of significance to archaeologists because environmental stressors,

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$</th>
<th>Skeletal Completeness</th>
<th>Orientation</th>
<th>Single/Multiple Interment</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.7079</td>
<td>(Cache)</td>
<td>N/A</td>
<td>Single</td>
</tr>
<tr>
<td>10-13v</td>
<td>0.7083</td>
<td>Cranial/Post-Cranial</td>
<td>North, South</td>
<td>Multiple</td>
</tr>
<tr>
<td>21</td>
<td>0.7091</td>
<td>Cranial/Post-Cranial</td>
<td>East</td>
<td>Single</td>
</tr>
<tr>
<td>23ii</td>
<td>0.7091</td>
<td>Cranial/Post-Cranial</td>
<td>South</td>
<td>Multiple</td>
</tr>
<tr>
<td>37</td>
<td>0.7077</td>
<td>Cranial/Post-Cranial</td>
<td>West</td>
<td>Single</td>
</tr>
</tbody>
</table>

Table 7.10. Variables related to non-local $^{87}\text{Sr}/^{86}\text{Sr}$ values that Freiwald (2011) described.
particularly drought, have been proposed as principal causes for multiple Maya
‘collapses’ and hiatuses (see Gill 2000; Gill et al. 2007; Kennet et al. 2012; Lucero
2002; Webster et al. 2007). Researchers have suggested that sites on the Vaca
Plateau, with their scarce water resources, would have been completely abandoned
during droughts causing ‘collapse’ (Polk et al. 2007). Radiocarbon dating of human
remains at Minanha has demonstrated that the site was not completely abandoned
during times of drought, however, were the droughts severe enough to deter
individuals from moving there?

In order to determine whether or not non-local individuals were moving to
Minanha during periods of drought, specimens were grouped according to radiocarbon
dates. Specimens whose 2σ radiocarbon dates spanned more than one chronological
period were counted in each period that the radiocarbon dates identified with the
exception of specimen dates spanning multiple drought periods – any specimen with a
radiocarbon date conforming to multiple periods of drought was only counted in the
drought group once. In addition, a few specimens had radiocarbon dates that intruded
into a new chronological period by one year – these specimens were not counted in
the new period groupings. Only drought periods two, three, and four were used
during statistical tests due to too few observations in drought period one.

Although it could not be tested whether or not individuals were leaving
Minanha during periods of drought, ⁸⁷Sr/⁸⁶Sr values were examined to determine if
non-locals were arriving at or living at Minanha during drought periods; however, the
small sample size precluded any significant statistical evaluation of the dataset.
Although statistical tests could not be run, of the five non-locals, two (specimens 3
and 23ii) lived during periods of drought at Minanha. The other three individuals
Table 7.1. Non-local individuals who lived through drought periods at Minanha.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Radiocarbon Date (2σ)</th>
<th>Time Period</th>
<th>Drought Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>100 B.C.E-C.E. 70</td>
<td>Terminal Preclassic</td>
<td>Drought One (100 B.C.E- C.E. 200)</td>
</tr>
<tr>
<td>10-13v</td>
<td>C.E. 420 - 640</td>
<td>Early, Middle Classic</td>
<td>Drought Two (C.E. 490 – 580)</td>
</tr>
<tr>
<td>21</td>
<td>C.E. 410 - 580</td>
<td>Early, Middle Classic</td>
<td>Drought Two (C.E. 490 – 580)</td>
</tr>
<tr>
<td>23ii</td>
<td>C.E. 900 - 1030</td>
<td>Early Postclassic</td>
<td>Drought Four (C.E. 900- 1150)</td>
</tr>
<tr>
<td>37</td>
<td>C.E. 1040 - 1260</td>
<td>Early, Late Postclassic</td>
<td>Drought Four (C.E. 900 - 1150)</td>
</tr>
</tbody>
</table>

(specimens 10-13v, 21, and 37) potentially lived during periods of drought at Minanha (see Table 7.11).

After the fall of the royal court, people continued to live at Minanha into the Early Postclassic before slowly abandoning it (Iannone 2005; Iannone et al. 2010). Because Minanha was not completely abandoned during the droughts and the population continued to flourish, it is possible that the collapse at Minanha was not caused by drought but by political events that predominantly affected the royal elite (Iannone 2005; Iannone et al. 2010). In addition, there was no change in diet during drought periods (Stronge 2012), suggesting that either the droughts were not severe enough to detrimentally affect the people at Minanha, or their methods of agriculture were robust enough to stave off the effects of drought. However the residents at Minanha responded to drought conditions, the effects of the drought were not severe enough to deter non-locals from moving there.

When examined in the context of Maya chronology, different periods of site development are observable at Minanha (see Table 4.1). These span from early development and population growth during the Late to the Terminal Preclassic, to the establishment of a royal court complex during the Late Classic, and finally to the
“Maya collapse” and near-abandonment of the site in the Terminal Classic and Postclassic periods. To examine whether a relationship exists between $^{87}\text{Sr}/^{86}\text{Sr}$ values and Maya chronological periods (i.e., whether non-locals were moving to Minanha more in one period vs. another), specimens were first grouped by chronological period. Most specimens have associated radiocarbon dates (n=17), although specimens 35, 36, and 38 were dated using ceramic styles. Specimens whose date range falls into more than one chronological period were grouped once in each period as indicated by their radiocarbon or ceramic dates. Unfortunately, the small group sizes created for statistical tests precluded any meaningful statistical results. However, some observations can be made concerning the non-local individuals at Minanha and the time periods in which they lived.

Despite the aforementioned periods of drought, people inhabited and developed the land at Minanha. Minanha was first settled during the Late Middle Preclassic between 600 B.C.E. and 400 B.C.E., and the earliest recovered architecture dates to C.E. 100-250 (Iannone 2005), during the first drought period recorded at the site. The earliest non-local individual in the sample (specimen 3) was interred within some of the earliest architecture at Minanha.

Throughout the following Early and Middle Classic (C.E. 250-675), the inhabitants at Minanha began to settle the Contreras Valley and construct agricultural terraces (Iannone and Schwake 2010; Macrae 2010). Alongside the development of the land, population and social complexity increased (Iannone and Schwake 2010; Macrae 2010; Mosher and Seibert 2006; Zehrt 2006). There are 12 individuals from the sample that potentially date to these periods, including the non-locals represented by specimens 10-13v and 21. During the Late Classic (C.E. 675-810), Minanha developed into perhaps the most important centre of the north Vaca Plateau (Iannone
2005, 2010). A royal court was established, the supporting population increased, and extensive construction projects were undertaken (Iannone 2005). No non-locals in the sample date to this period, but six locals from the sample potentially date to this period. However, Minanha’s fluorescence was not long-lived – only a century later it fell into decline, its epicentral court complex abandoned and filled-in and its overall population diminished (Iannone 2005). There are five individuals in the sample that potentially date to this period, but none are non-local. People continued to inhabit the area until it was completely abandoned during the Late Postclassic (C.E. 1200-1525). Seven individuals in the sample potentially date to this period, including the non-locals represented by specimens 23ii and 37. Interestingly, no non-local individuals date to the period of Minanha’s prominence during the Late Classic (C.E.675-810), despite reported population increases (Iannone 2005). However, this is most likely due to the small sample size and SARP’s 15% sampling strategy (see Chapter 4) implemented within the Contreras Valley, the area that would have seen the most growth. Overall though, the data do show that individuals were moving to Minanha throughout different periods, regardless of drought or social instability.

### 7.5 Elite mobility

Epigraphic and iconographic evidence from the Maya cultural area suggests that there was movement between different centres by elites and royals, and Price et al. (2010), performing strontium isotope analysis on the purported remains of K’inch Yax K’uk’ Mo’, presented $^{87}\text{Sr}/^{86}\text{Sr}$ values that corroborated Maya epigraphic records. No such records of elite mobility have been discovered at Minanha, nor do other centres make reference to elites or royals re-locating to Minanha.
Minanha’s royal court was founded during the Late Classic (C.E. 676-810) and terminated during the Terminal Classic (C.E. 811-900). Of the 20 individuals sampled for analysis, three were interred within the epicentre and likely date to the period of royal rule at Minanha. None of these three individuals has a non-local strontium isotope value; as such, the data available do not identify migration during this time period (see Table 7.1). However, the sample size for this time span is far too small to allow us to comment on whether the royal court was founded by a non-local or local population.

### 7.6 Local individuals

The results suggest that people were migrating to Minanha at different time periods, regardless of socio-political or environmental events. Due to the small sample size, it is unknown if immigration to Minanha increased or decreased during certain periods. However, the findings of this study are consistent with those of other published papers in that the proportion of the sample that is non-local is between 10-30% (Freiwald 2011; Price et al. 2010; Wright et al 2005a). In addition, the limited range of $^{87}\text{Sr}/^{86}\text{Sr}$ values of the Minanha dataset supports the conjecture that most population movement occurred between neighbouring regions (Freiwald 2011:353).

The local individuals, comprising 75% of the sample, exhibit a range of values (0.7083-0.7090) that is limited enough to represent the range of biogenic $^{87}\text{Sr}/^{86}\text{Sr}$ at a site but varies enough to take into account differential access to local resources (Emery 2003, 2007; Pohl 1985; Stronge 2012) and individual idiosyncrasies.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.7088</td>
</tr>
<tr>
<td>19</td>
<td>0.7084</td>
</tr>
<tr>
<td>36</td>
<td>0.7090</td>
</tr>
</tbody>
</table>

**Table 7.12.** Specimens dating to periods of royal rule at Minanha.
However, it is possible that some individuals identified as locals in the sample were non-local to Minanha. For example, specimens 7 and 19 exhibited a dental modification type more common to Guatemala and the Peten region (Williams and White 2005), but have $^{87}\text{Sr}/^{86}\text{Sr}$ values that do not coincide with those areas. Such cases may be indicative of multiple instances of mobility during one lifetime. Only one molar was analysed from each individual in the sample; these molars represent a discreet developmental period during life. If mobility occurred before or after those periods of development, the individual’s $^{87}\text{Sr}/^{86}\text{Sr}$ value would not reflect this mobility.

7.7 Research Summary

This thesis project identified non-local individuals interred at Minanha through the use of strontium isotope analysis. An outlier method was used to determine which individuals were non-locals as using a baseline method based on published regional $^{87}\text{Sr}/^{86}\text{Sr}$ maps of the Yucatán was unsuccessful – the majority of the $^{87}\text{Sr}/^{86}\text{Sr}$ values from Minanha did not fit within the expected range predicted from the regional maps. The percentage of non-local individuals identified in the sample population (25%) is consistent with non-local percentages reported from other ancient Maya sites. Furthermore, the non-local individuals have $^{87}\text{Sr}/^{86}\text{Sr}$ values that correspond to locales within 10-20 km of Minanha, which is consistent with the conjecture that mobility in the Maya subarea occurred mostly within relatively small distances. In addition, the data suggest that non-local individuals were arriving at Minanha during periods of drought and political/socioeconomic unrest, which corresponds with Stronge’s (2012) findings arguing that drought and periods of unrest were not severe enough to alter diet. However, small group sizes precluded the execution of statistical testing for many variables. The statistical tests that were possible suggest that there were no
shared identifiable attributes between non-local individuals – they were buried differently at different times and in different areas. However, the burial contextual information for each individual at Minanha was enriched by the inclusion to that data of $^{87}\text{Sr}/^{86}\text{Sr}$ values.

7.8 Limitations

The predominant limitation of this thesis project was the sample size. The moist, tropical climate of the Maya subarea is not conducive to the preservation of biological tissues; furthermore, Maya burials are often looted, which further contributes to the loss of human remains. As such, the recovery of human remains at ancient Maya sites is markedly circumscribed, and for this project, resulted in a small sample size of $n = 20$. The individuals constituting this sample spanned over one millennium and had many varying attributes characterising each of them. This made it impossible to perform many meaningful statistical analyses because group sizes were too small.

However, on the whole, 25% of the sample population was identified as non-local. This is a significant portion of the population, and although further general arguments concerning mobility at the population level cannot be made, it can be postulated that non-local individuals comprised a measurable fraction of the population at Minanha. It is possible that mobility in the Maya region was not stagnant, but active, and was most likely executed by individuals moving between neighbouring regions.

7.9 Future directions

The $^{87}\text{Sr}/^{86}\text{Sr}$ values generated from Minanha are important for the strontium isotope mapping of the Maya subarea. By continuing to report $^{87}\text{Sr}/^{86}\text{Sr}$ values throughout the Yucatán, researchers will have a regional map to refer individual
However, this study emphasises the importance of collecting baseline $^{87}\text{Sr}/^{86}\text{Sr}$ values from the site itself – the strontium isotope values of the Minanha individuals did not fit in the expected $^{87}\text{Sr}/^{86}\text{Sr}$ range predicted from regional maps. To validate the Minanha local strontium isotope ratio, baseline samples should be collected from the site itself.

In addition, strontium isotope values can be further validated by performing oxygen isotope analysis on the same samples. Oxygen isotope analysis provides similar information to that obtained from strontium isotope analysis, namely that oxygen isotopes in hydroxyapatite reflect the oxygen isotope values from geographic locales. By performing oxygen isotope analysis on the same sample, the results of the strontium isotope analysis can be strengthened.
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