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Exploring the Movement of People in Postclassic and Historic Period Lamanai Using Stable Isotopes

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A thesis submitted in partial fulfillment of the requirements for the degree in Master of Arts
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(Thesis format: Monograph)

by

Alicia E. Donis

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of the requirements for the degree of
Master of Arts

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Abstract

The location of the Maya site of Lamanai on the New River Lagoon in northern Belize strategically situated it to participate in both coastal and inland trade routes and communication. This study of human burials at Lamanai examines the phosphate-oxygen isotope compositions of bone and enamel, which reflect drinking water and hence climatic zones, oxygen- and hydrogen-isotope compositions of modern local water, which provide a baseline for drinking water, and carbon- and nitrogen-isotope compositions of bone collagen, which reflect diet. The combination of isotopic, mortuary, osteological, and artifactual data is used to explore mobility at Lamanai during the Postclassic and Historic periods. While these data suggest some mobility, most movement likely occurred within the surrounding lowland region. The origin of Postclassic individuals buried in an unusual face-down position (VPLF) was also investigated. The VPLF group demonstrates variability in demographics and residential history, and its appearance possibly reflects an ideological shift.

Keywords

Maya, Belize, Lamanai, stable isotopes, carbon, nitrogen, oxygen, bioapatite, phosphate, collagen, bone, enamel, mobility, diet, burial position

Dedication

To my parents, Jim and Elizabeth Donis, for their never-wavering love, support, and confidence in me.

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Chapter 1

1   Introduction

1.1   Introduction and Goals

The ancient Maya site of Lamanai, located on the banks of the New River Lagoon in modern-day northern Belize, has one of the longest known continuous occupations in the Maya Lowlands. Lamanai is exceptional because of its rich material remains, its survival of the Classic Maya 'collapse', and its occupation during the Spanish Colonial period. Although they are little known at other sites, these periods of transition are well represented at Lamanai (Graham 2004). Lamanai was also strategically situated to participate in both coastal and inland trade routes and lines of communication, connecting it to events occurring at regional levels and beyond. As such, it has great anthropological potential for the study of Maya mobility[1], especially for studies investigating the possibility of change in patterns over time.

The Postclassic period (ca. AD 950–1550) in the Maya world was once regarded as a time of "decline, decadence, and depopulation" (Chase and Rice 1985). However, our understanding of this time in Mesoamerican history is changing. The Postclassic is beginning to be recognized as a time characterized by the increased volume and diversity of interregional and international trade extending from central Mexico through the Maya region and into the Caribbean and South America. The movement of goods observed in the archaeological record has implications for the mobility of people.

The events following the arrival of the Spanish, marking the beginning of the Historic period, also had implications for movement in the Maya world. Along with the introduction of new diseases, slave raids, and violent conquest efforts, the Spanish invaders also imposed religious, political, and economic changes. Through application of

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[1] In this study the term *mobility* is understood as the movement of an individual (or group of individuals) from place to place, and it includes movement both permanent (e.g. residential relocation) and impermanent (e.g. travel for trade).

stable isotope analysis to a portion of Lamanai's Postclassic and Historic population, this study aims to investigate mobility during these times.

Isotopic analysis provides a window into the past at the level of the individual, humanizing the past and providing direct evidence for relocation. It is based on the premise that we are what we eat and drink. The isotopic composition of our food and water is incorporated into bones and teeth during mineralization. Enamel does not remodel and, therefore, reflects childhood environments, whereas bone continuously remodels, reflecting residential environments in later years of life. In many cases, analysis of both tissues enables the detection of relocation during individual life histories. This study of human burials at Lamanai examines the phosphate-oxygen isotope compositions of their bone and enamel, which reflect drinking water and hence climatic zones, and carbon- and nitrogen-isotope compositions of bone collagen, which reflect diet (which can vary by region, group preference, and/or status). The combination of the isotopic data, along with relevant mortuary, osteological, and artifactual information are used to investigate mobility at Lamanai during the Postclassic and Historic periods.

Within the overarching goal of studying mobility during the later part of Lamanai's history, the thesis also addresses a number of more specific questions: (1) how did major developments in the Maya world possibly affect mobility, (2) are there differences in residential history[2] among individuals interred within different contexts (i.e., residential versus ceremonial structures), (3) are there sex- and/or age-related patterns of mobility, and (4) can geographic identity[3] be used to better understand unusual burial patterns? The burial pattern of particular interest is the VPLF position, which is an intriguing face-down, legs bent back pose found in the Postclassic period.

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[2] "Residential history" is understood here as the record of an individual's residence during their lifetime, but does not include non-permanent movement (e.g. travel for trade).

[3] Geographic identity is being determined in this study primarily from skeletal isotopic compositions, along with additional lines of evidence of locational affiliation such as cranial and dental modifications.

1.2   Thesis Organization

The first three chapters outline the theoretical background to the study (Chapter 2), the study site and sample (Chapter 3), and the methodology used (Chapter 4). Chapter 2 reviews the basic principles of stable isotope science and provides the theoretical background for oxygen-, carbon-, and nitrogen-isotope analysis in anthropological applications. A Maya-area specific dietary carbon- and nitrogen-isotope model is also presented in Chapter 2, together with a discussion of diagenesis (i.e., post-mortem alteration of skeletal tissues). Chapter 3 describes Lamanai's location and environment, along with its culture and excavation histories. After a brief review of burial patterns in the Maya area and at Lamanai in particular, the individuals available for study, the previous work done at the site, and the selection of both the skeletal and water samples (to inform Lamanai's drinking water baseline) are described.   Chapter 4 presents the methodology used for preparation and analysis of phosphate-oxygen isotope compositions of the skeletal material, the extraction and subsequent analysis of collagen for its carbon- and nitrogen-isotope compositions, the assessment of diagenesis, and the collection and hydrogen- and oxygen-isotope analysis of water samples.

Chapter 5 presents and discusses the results of this study. It begins with the assessment of post-mortem alteration and a brief examination of the modern water isotopic data collected in and around Lamanai. A more detailed evaluation of the phosphate-oxygen isotopic data follows. This evaluation includes: (1) overall comparisons among tissue type, time period, sex, and age, and (2) examination of the isotopic data by time period for sex, age, and other, more time-period specific, considerations (e.g., structure type in the Postclassic). This study's findings for phosphate-oxygen are also compared with those of earlier Lamanai mobility studies (Howie et al. 2010; White et al. 2009), and the sample's within-lifetime variability and fit to the pre-existing Lamanai baseline are evaluated. The new dietary data (carbon- and nitrogen-isotope data from collagen) for Lamanai are then presented and interpreted within the context of a larger dataset made possible by combination with results from previous studies (Howie et al. 2010; White and Schwarcz 1989). The VPLF individuals are then discussed in light of these data, data from prior studies, and some additional lines of evidence (i.e., cranial modification,

dental modification, and grave goods). Chapter 6 summarizes the larger findings of this study and suggests some potential avenues for further research.

Chapter 2

2 Theoretical Background

The following chapter presents the theoretical background necessary to this study. It begins with an introduction to the basics of stable isotopes and the tissues being used in this study, before moving on to discuss, in turn, the theoretical background of oxygen-, carbon-, and nitrogen-isotope analysis in anthropology, including interpretive issues that may be encountered with each. After a presentation of a Maya-area specific dietary carbon- and nitrogen-isotope model, the chapter concludes with a discussion of post-mortem alteration of skeletal tissues.

2.1 Stable Isotopes

Isotopes of an element have the same number of protons and electrons, but a different number of neutrons. Unlike radioactive isotopes, often used in archaeology for dating purposes, stable isotopes do not decay to other isotopes over time. As atomic mass is determined by the number of protons and neutrons, isotopes of an element vary in their masses. This mass difference slightly affects physical and chemical properties and, as a result, heavier isotopes (those with a higher mass) usually react slightly more slowly than lighter isotopes (those with a lower mass). The difference this produces in isotopic ratios is called fractionation. Fractionation can occur under equilibrium or non-equilibrium conditions, such as state changes and biological reactions (Faure and Mensing 2005). For example, as water evaporates, molecules containing the lighter oxygen isotopes (^{16}O) are more likely to be incorporated into water vapour than those containing the heavier oxygen isotopes (^{18}O), leaving the former enriched in ^{18}O.

Isotopic composition refers to abundance ratios relative to the ratios of those same isotopes in an internationally standard reference material. The resulting values are reported in delta (δ) notation and are expressed in per mil (‰). The δ-value is defined as:

$$\delta = [(R_{sample} - R_{standard}) \div R_{standard}]$$

where R is the ratio of heavy to light isotopes (Coplen 2011). For oxygen- (δ^{18}O) and hydrogen-isotope analysis (δ^2H) the standard reference material is Vienna Standard Mean Ocean Water (VSMOW), while Vienna Pee Dee Belemnite (VPDB) is the carbon-isotope (δ^{13}C) standard (Coplen 1994). The nitrogen-isotope (δ^{15}N) reference standard is atmospheric nitrogen (AIR) (Mariotti 1983).

2.2 Skeletal Tissues

As bones and teeth are the components of the human body most likely to be preserved, they are often central to archaeological studies of human remains. By weight, bone is composed of ~ 60–70% inorganic (mineral) and ~ 20–30% organic material (Reiche et al. 2002). Collagen molecules, which make up the majority of bone's organic component, are organized into long, rope-like structures called fibrils. Their organization, structure, and bonding are responsible for the tensile strength of bone, and form the latticework into which the mineral component of bone is deposited (White 2000). Bone mineral is commonly called hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$), although its composition often differs from this formula as many substitutions can be made (LeGeros 1991; Sandford 1993; Sillen 1989). Carbonate (CO_3^{2-}), from which many studies obtain dietary carbon isotopes, is actually an impurity, as it substitutes in either the phosphate position (type B carbonate) or, less commonly, the hydroxyl group position (type A carbonate) in the apatite[4]. As a result of its variable formula, bone hydroxyapatite is typically referred to as biological apatite or bioapatite. Bioapatite is also the primary component (~ 97%) of tooth enamel (LeGeros 1991).

Bone is a dynamic, living tissue that is constantly being remodeled, and, as such, it reflects a weighted average of isotopic compositions over the last years of life. Bone turnover in adult cortical bone averages ~ 2 to 4 % per year (Hedges et al. 2007; Manolagas 2000; Parfitt 1983; Valentin 2002). Turnover rate is affected by many factors, including bone type (e.g., trabecular remodels faster than cortical) (Manolagas 2000; Sealy et al. 1995; Valentin 2002), age (e.g., children's bones remodel faster than

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[4] Carbonate ions also adsorb onto the surface of the crystals.

adults) (Beaumont et al. 2013; Frost 1969; Hedges et al. 2007; Valentin 2002), sex (e.g., before the age of 20 years, male bone turnover is faster) (Hedges et al. 2007), and stress or injury (Martin 2000; Schaffler and Burr 1984). Tooth enamel, however, does not remodel after its mineralization during tooth crown formation. Tooth mineralization commences in utero around 4 months and continues to the age of 16 (Moorrees et al. 1963; Schour and Massler 1941), so it is childhood isotopic compositions that are retained in teeth. However, since different teeth form at different times on a relatively firm schedule (Table 2.2-1), each tooth can provide information about an individual at different ages. These differences in the information accessible from bones and teeth, as well as between teeth, make studies that provide analysis of multiple samples from one individual more comprehensive.

Table 2.2-1 Human Tooth Enamel Formation Timing

		Deciduous		Permanent	
		Initial Cusp Formation	**Crown Complete**	**Initial Cusp Formation**	**Crown Complete**
Upper	1st Incisor	13.0–16.0 wks in utero	1.5 mths	0.25–0.3 yrs	4.0–5.0 yrs
	2nd Incisor	14.7–16.5 wks in utero	2.5 mths	0.8–1.0 yrs	4.0–5.0 yrs
	Canine	15.0–18.0 wks in utero	9.0 mths	0.3–0.4 yrs	6.0–7.0 yrs
	1st Premolar	—	—	1.5–2.0 yrs	5.0–6.0 yrs
	2nd Premolar	—	—	2.0–2.5 yrs	6.0–7.0 yrs
	1st Molar	14.5–17.0 wks in utero	6.0 mths	0.0 yr	2.5–3.0 yrs
	2nd Molar	16.0–23.5 wks in utero	11.0 mths	2.5–3.0 yrs	7.0–8.0 yrs
	3rd Molar	—	—	7.0–10.0 yrs	12.0–16.0 yrs
Lower	1st Incisor	13.0–16.0 wks in utero	2.5 mths	0.25–0.3 yrs	4.0–5.0 yrs
	2nd Incisor	14.7 wks in utero	3.0 mths	0.25–0.3 yrs	4.0–5.0 yrs
	Canine	16.0 wks in utero	9.0 mths	0.3–0.4 yrs	6.0–7.0 yrs
	1st Premolar	—	—	1.5–2.0 yrs	5.0–6.0 yrs
	2nd Premolar	—	—	2.0–2.5 yrs	6.0–7.0 yrs
	1st Molar	14.5–17.0 wks in utero	5.5 mths	0.0 yr	2.5–3.0 yrs
	2nd Molar	17.0–19.5 wks in utero	10.0 mths	2.5–3.0 yrs	7.0–8.0 yrs
	3rd Molar	—	—	7.0–10.0 yrs	12.0–16.0 yrs

Source: Data from Hillson 1996:123–124.

2.3 Oxygen

Since its first 'anthropological' use by Schwarcz and colleagues (1991) in their study of the origins of War of 1812 soldiers, oxygen isotopic analysis has received much attention

in studies of past human movement (e.g., Budd et al. 2004; Evans, Chenery, and Fitzpatrick 2006; Evans, Stoodley, and Chenery 2006; Knudson and Price 2007; Prowse et al. 2007; White et al. 1998; White et al. 2002; White, Spence, et al. 2004; White, Storey, et al. 2004; White et al. 2007). The oxygen isotopic composition of imbibed water is affected by environmental and climatic factors (such as temperature, elevation, humidity, and latitude) (Dansgaard 1964). This variability is incorporated into body water, which equilibrates with the phosphate and carbonate in enamel and bone at a constant body temperature (Bryant et al. 1996; Levinson et al. 1987; Longinelli 1984; Luz et al. 1984). Thus, the oxygen-isotope composition of skeletal tissues provides an environmental signal that aids in identification of geographic origin[5] and residential history (Ayliffe and Chivas 1990; Koch et al. 1989; Land et al. 1980; Podlesak et al. 2008). Individuals who do not have $\delta^{18}O$ values typical of those who are archaeologically defined as "local" are assumed to be from a different geographic region (White et al. 2002:219). If other studies have been done in the surrounding areas, it may be possible to posit the geographic origins of these "foreigners", but when assessing geographic origin isotopic data is largely exclusionary.

Oxygen is present in both phosphate and carbonate in bioapatite, and oxygen-isotope compositions of phosphate ($\delta^{18}O_p$) and carbonate ($\delta^{18}O_{sc}$) have been found to be correlated, despite some internal and inter-species variability (Bryant et al. 1996; Chenery et al. 2012; Iacumin et al. 1996; Martin et al. 2008; Pellegrini et al. 2011). Most studies of mammalian oxygen isotope composition have focused on phosphate. This is primarily because of the strength of the phosphorous-oxygen bond, which "is so strong that lengthy and harsh chemical procedures are required to extract the oxygen and convert it to CO_2 for isotopic measurement" (Sponheimer and Lee-Thorp 1999:724). It is thought that the oxygen found in structural carbonate is more likely to be affected by diagenesis (post-mortem alteration), because it is less tightly bound to the bioapatite structure, and it is generally accepted that $\delta^{18}O_p$ is less susceptible to diagenesis than $\delta^{18}O_{sc}$ (Chenery et al. 2012; Land et al. 1980; Lee-Thorp 2002; Nelson et al. 1986;

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[5] The term *geographic origin* relates specifically to the location where an individual was born/spent their early years of life.

Schoeninger and DeNiro 1982). Although still more resistant, $\delta^{18}O_p$ can also experience alteration, particularly in cases of microbial attack (Ayliffe et al. 1994; Blake et al. 1997; Kolodny et al. 1996; Longinelli 1996; Sharp et al. 2000; Tütken et al. 2008; Zazzo, Lécuyer, and André 2004; Zazzo, Lécuyer, and Mariotti 2004). (For further discussion of diagenesis see section 2.7).

2.3.1 Interpretative Issues

In addition to questions concerning the use of phosphate- versus carbonate-oxygen isotopic measurements, there are some well-recognized interpretative issues worthy of note. First of all, within any population, there is an expected level of inter-individual variability[6]. This leads to concerns that natural intrapopulational variability may obscure the identification of foreign individuals. To address this concern, it is necessary to establish a control sample, which has been done, for example, in Mesoamerica, where the expected intrapopulational variability is approximately 2 ‰ (White et al. 1998; White et al. 2000; White, Spence, et al. 2004; White, Storey, et al. 2004).

There are a number of factors that can cause oxygen-isotope compositions to vary within a population, and, while some intrapopulational variability should be expected, potential contributing factors should still be acknowledged. For example, variation in the isotopic compositions of different locally available water sources can contribute to intrapopulational variability. Changing seasonal conditions can also affect the $\delta^{18}O$ values of environmental water (Gat 1996). A number of intra-tooth studies using mammals have demonstrated that different $\delta^{18}O$ values can be representative of seasonal climatic changes (Fricke and O'Neil 1996; Fricke et al. 1998; Gadbury et al. 2000), and if human teeth are similarly affected by seasonal changes, intra-tooth variation may be misrepresented as geographic relocation. However, if whole teeth are used, this seasonal variability will likely be averaged through the time of tooth formation and therefore be masked (White et al. 2000).

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[6] Intra-species variation also occurs as $\delta^{18}O$ values are affected by such factors as species size and physiology, including metabolic rate and the expulsion of compounds containing oxygen such as breath vapour, perspiration, urine, and feces (Bryant and Froelich 1995; Kohn 1996; Kohn et al. 1996; Sponheimer and Lee-Thorp 1999).

Another factor that may affect oxygen isotope compositions is the δ^{18}O values of food consumed. Although drinking water is the principal influence on the isotopic composition of body water (and thus body oxygen) (Longinelli 1984), oxygen chemically bound in food, as well as water obtained from food, can impact an individual's δ^{18}O values (e.g., cellulose and leaf water ^{18}O-enrichment in plants can be passed on to the animals that consume them) (Bocherens et al. 1996; Brettell et al. 2012; Daux et al. 2008; Fricke et al. 1998; Sponheimer and Lee-Thorp 1999). However, as long as it is food from the local environment, in most cases this should not cause a problem in distinguishing between local and non-local individuals. Even if there were certain sections of the population consuming imported foods (i.e., elites), large quantities would likely be necessary to have a significant impact on their isotopic values, and thus, input of foreign foods would likely be subsumed within the range of intrapopulational variability and would be a minor source of error (White, Spence, et al. 2004; White, Storey, et al. 2004; White et al. 2007). Water storage techniques and preparation of water sources (e.g., boiled beverages or stews) must also be considered as the consumption of significant quantities of altered water may result in δ^{18}O values different than expected based on climatic assumptions alone (Brettell et al. 2012; Daux et al. 2008; Knudson 2009; Wright 2012).

It is also important to recognize that there is an enrichment in ^{18}O that has been observed in breastfeeding children, which has been utilized to study infant feeding behaviour (e.g., White et al. 2000; Williams et al. 2005; Wright and Schwarcz 1998, 1999). This needs to be considered not only when dealing with the skeletal remains of infants, but also when analyzing teeth formed when an individual was breastfeeding. Studies done in Mesoamerica suggest that the δ^{18}O values of bone from individuals less than three years of age, along with deciduous second molars and permanent first molars, should be adjusted downward by 0.7 ‰; for premolars and canines 0.35 ‰ is recommended to correct for this breastfeeding ^{18}O-enrichment (White et al. 2000; White, Spence, et al. 2004; White, Storey, et al. 2004; White et al. 2007).

It is clear that there are a number of factors that need to be considered when applying oxygen-isotope data to the study of mobility. Although not explicitly discussed above,

the possibility that climate fluctuations over time altered the isotopic composition of precipitation should also be considered. When attempting to identify probable place of origin it is ideal to use coeval burial populations (Budd et al. 2004) and/or to use multiple lines of evidence, both archaeological (e.g., burial context) and other types of isotopic evidence.

2.4   Carbon

Isotopic methods also have a long history of being applied to understanding diets of past peoples, as the isotopic composition of consumed foods is reflected in the body's tissues (i.e., 'you are what you eat') (DeNiro and Epstein 1978, 1981). Carbon- (δ^{13}C) and nitrogen- (δ^{15}N) isotope compositions are regularly used for dietary reconstruction.

Carbon was the first element used in archaeological stable isotope studies, logically following from archaeologists' familiarity with it from radiocarbon dating (Katzenberg 2000). One of its first archaeological applications was in identifying maize consumption (van der Merwe and Vogel 1978). This is because maize, like several other tropical grasses (sorghum, millet, and sugar cane), uses a different photosynthetic pathway than most plants from temperate climates. The level of discrimination against ^{13}C (in favour of ^{12}C) between these pathways results in largely non-overlapping δ^{13}C values. Tropical grasses, or C$_4$ plants, have δ^{13}C values around –12 ‰, whereas C$_3$ plants average ~ –25 ‰ (Schwarcz and Schoeninger 2012). However, the burning of fossil fuels over the last few hundred years has shifted the δ^{13}C values of modern plants due to the release of ^{12}C-rich carbon dioxide into the atmosphere; therefore, it is assumed here that the δ^{13}C values of ancient plants were 1.5 ‰ more positive than their modern equivalents (also referred to in literature as the industrial or Suess effect) (Marino and McElroy 1991).

Stable carbon isotopic data are also valuable in coastal areas where they are used to test hypotheses concerning the importance of marine versus terrestrial food contributions to diet (Blake et al. 1992; Chisholm et al. 1982; Keegan and DeNiro 1988; Walker and DeNiro 1986). This is possible due to the difference in δ^{13}C values between each food web's primary source of carbon. The main source of carbon for terrestrial organisms is atmospheric CO_2, whereas marine organisms' main source is dissolved carbonate, which

is enriched in ^{13}C by ~ 7 ‰ in comparison (Schwarcz and Schoeninger 2012; Smith and Epstein 1971).[7]

Studies have been undertaken to determine the difference between the δ^{13}C values of dietary input and various body tissues. As the δ^{13}C value of bone collagen (δ^{13}C$_{col}$) has been found to be approximately 5 ‰ greater than diet, the phrase "You are what you eat +5 ‰" has been coined (Katzenberg 2000:314). Before 1993, dietary studies assumed that δ^{13}C$_{col}$ values represented the carbon in an animal's whole diet (i.e., proteins, carbohydrates, and lipids). However, further experimentation and examination has shown that δ^{13}C$_{col}$ values primarily reflect the carbon in dietary protein due to preferential routing (Ambrose and Norr 1993; Froehle et al. 2010; Jim et al. 2004; Tieszen and Fagre 1993b), although in protein-deficient diets, there is some question as to whether collagen may, in fact, reflect values closer to whole diet (Kellner and Schoeninger 2007; Schwarcz 2000). For a better understanding of whole diet, studies often also look at the mineral portion of bone (and enamel), because (as it is currently understood) the δ^{13}C value of structural carbonate (δ^{13}C$_{sc}$) represents the carbon in an animal's whole diet (Ambrose and Norr 1993; Howland et al. 2003; Jim et al. 2004; Schwarcz 2000; Tieszan and Fagre 1993b). The combination of these two isotopic signatures for carbon sources are particularly useful in situations when low protein resources may be important to diet (e.g., sugar consumption in the Marianna Islanders – Ambrose et al. 1997) and have been plotted against each other in meta-analyses (Froehle et al. 2010; Kellner and Schoeninger 2007) of past studies in order to reveal both the main energy and main protein source of a subject's diet.

Trophic level, which is the position an organism occupies in a food web (e.g., carnivores have a higher trophic level than herbivores), can also be explored using carbon isotopic data. Although the small increase in δ^{13}C values of ~ 1 ‰ between trophic levels is of questionable use (Ambrose and DeNiro 1986a; Ambrose et al. 1997:34; DeNiro and Epstein 1978; Schoeninger 1985), it has been suggested that δ^{13}C values can be used to track the introduction of solid food in weaning infants (Fuller et al. 2006). Alternatively,

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[7] Freshwater organisms generally fall in the range of C$_3$ plants (Ambrose 1993).

the difference between $\delta^{13}C_{sc}$ and $\delta^{13}C_{col}$ values ($\Delta^{13}C_{sc-col}$) has been used as a measure of an organism's trophic level, as studies have shown this spacing to average 7 ‰ for herbivores, 5 ‰ for omnivores, and 3–4 ‰ for carnivores (Krueger and Sullivan 1984; Lee-Thorp et al. 1989). However, the interpretation of spacing is not always that straightforward, because protein source also has an important impact on this relationship (Froehle et al. 2010; Kellner and Schoeninger 2007; Lee-Thorp et al. 1989; Tieszen and Fagre 1993b). Nitrogen isotopic data (see below) and contextual information can often be used to clarify interpretation.

2.4.1   Interpretative Issues

Along with the interpretative issues raised above, there are other factors that should be considered when using $\delta^{13}C$ values to reconstruct paleodiet. For example, local environmental factors (e.g., water availability, temperature, and light intensity) can cause variations in plant $\delta^{13}C$ values (Ambrose 1993; Casey and Post 2011). For this reason, it is important to establish the $\delta^{13}C$ values of local resources, as opposed to relying on global means. In many areas of the world, isotopic analyses have been done, data compiled, and food webs built (e.g., Maya region – Metcalfe 2005; J. Metcalfe et al. 2009; White, Pendergast, et al. 2001; White, Pohl, et al. 2001; Williams et al. 2009). (Refer to section 2.6 for the food web created for this study).

In some areas of the world, in addition to the two general types of plants (C_3 and C_4) discussed above, there is also a third class of plant whose $\delta^{13}C$ values need to be taken into consideration when constructing food webs. This group of plants, which includes cacti and succulents, use the Crassulacean Acid Metabolism pathway (CAM). CAM plants make use of both C_3 and C_4 methods of CO_2 fixation, which results in overlapping isotopic compositions with the other two groups (Bender et al. 1973; Schwarcz and Schoeninger 2012). These overlapping compositions could mask the dietary contributions of C_3 and C_4 plants if CAM plants were consumed in significant quantities (e.g., Warinner et al. 2013). Many studies assume that CAM plants were not making a significant contribution based on the availability of edible varieties in the study area (e.g., in the Maya world – Metcalfe 2005; Olsen 2006; White, Pendergast, et al. 2001).

Other dietary patterns that may confound interpretations of carbon-isotope data include the consumption of ^{13}C-enriched meat and/or fish. If animals being exploited by human groups are consuming C_4 plants, the δ^{13}C values of their tissues will be higher, which will, in turn, be reflected in human bone collagen (Katzenberg 1989). In addition, because marine, reef, and estuarine fish tend to have high δ^{13}C values, their range can overlap with the range of terrestrial C_4 plants (Coyston et al. 1999; Walker and DeNiro 1986). In such cases, the use of nitrogen-isotope data can help to sort out some of the answers that cannot be determined decisively with the use of bulk collagen carbon-isotope analysis alone. It is clear that carbon isotopic data have the potential to provide a wealth of information about diets in the past, but there are a number of interpretative issues that need to be considered.

2.5   Nitrogen

Now often paired in archaeological studies with carbon isotopes, nitrogen was the second element used in human paleodiet research (Katzenberg 2000). It can be used to establish the source of dietary protein, as well as an organism's trophic level (which can clarify bulk collagen carbon-isotope interpretations). Plants demonstrate nitrogen isotopic variation because different plants obtain nitrogen in different ways (for further review of plant nitrogen isotopic variation see Szpak et al. 2013). Many plants derive their nitrogen from nitrogen-containing compounds in the water and soil of the immediate environment. Other plants, such as blue-green algae and many legumes, are part of a symbiotic relationship with nitrogen-fixing bacteria that convert atmospheric nitrogen into a form usable by the plant. These nitrogen-fixing plants have nitrogen-isotope compositions similar to that of the atmosphere (~ 0 ‰) (Delwiche and Steyn 1970) and, as a result, generally have lower δ^{15}N values than other plants (Koch et al. 1994). Climate can also affect δ^{15}N values (Ambrose 1993). For example, plants in hot, dry environments tend to have higher δ^{15}N values than those in cooler, wetter environments. Therefore, to have the best understanding of the nitrogen isotopic distribution within a particular ecosystem, it is essential to establish the δ^{15}N values of local plants (as discussed above for carbon).

Differences in the δ^{15}N values of plants are reflected in the tissues of the animals that consume them. This is part of the reason that higher δ^{15}N values (+10 ‰ to +13.5 ‰) are

seen in marine animals than in terrestrial herbivores (~ +7 ‰) or carnivores (~ +9 ‰), as marine plants have higher δ^{15}N values than terrestrial plants (Coyston et al. 1999; Olsen 2006). However, marine animals from reefs have δ^{15}N values more similar to terrestrial organisms than other marine organisms, because the blue-green algae that form the base of these ecosystems are nitrogen-fixing, and are therefore ^{15}N-depleted compared to other marine plants (Capone and Carpenter 1982). Most marine animals also have higher δ^{15}N values than terrestrial animals because there are more trophic levels in marine food webs. As nitrogen moves from one trophic level to the next, the δ^{15}N values of collagen increase by approximately 3 to 4 ‰ (DeNiro and Epstein 1981; Post 2002; Schoeninger 1985). Because of this, δ^{15}N values are also useful in studying ancient breastfeeding practices and weaning timing, as breastfeeding infants occupy one trophic level above their mothers since the infants are essentially consuming their mother's tissues (Dupras et al. 2001; Fuller et al. 2006; Herring et al. 1998; Richards et al. 2002; Schurr 1998; Schurr and Powell 2005).

2.5.1   Additional Interpretative Issues

Although nitrogen isotopic compositions of tissues can provide insight into many diet-related questions, as well as supporting and clarifying interpretations based on δ^{13}C values, interpretation of δ^{15}N values is also not always clear-cut. (While a number of the possible interpretative issues are discussed here, Hedges and Reynard 2007 provide a further review.) The commonly assumed "standard" trophic enrichment that is frequently applied to human studies is 3 ‰ (Lee-Thorp 2008); however, it is not known if this is the correct offset for humans (Hedges and Reynard 2007; O'Connell et al. 2012). Part of this uncertainty arises because ^{15}N-enrichment in collagen can be affected by a number of factors including species physiology, behavior, climate, and environment (Ambrose 1986; Ambrose and DeNiro 1986b; Casey and Post 2011; Heaton et al. 1986; Sealy et al. 1987). For example, animals residing in cool, wet environments have different water acquisition and conservation strategies than those in hot, dry environments. There is evidence to suggest that drought-tolerant animals have higher δ^{15}N values, as well as larger nitrogen-isotope fractionations between tissues and diet than do other animals (Ambrose 1986, 1993). The use of fertilizer can also affect δ^{15}N values of treated crops,

and this enrichment then travels through the food web, which can make it appear that groups are consuming more meat than they actually are if the 'manuring effect' is not taken into account (Bogaard et al. 2007; Szpak, Longstaffe, et al. 2012; Szpak, Millaire, et al. 2012).

There are also situations where members of the same species consuming identical diets can have different δ^{15}N values. This variation results from fluctuations in the body's nitrogen homeostasis, which can be affected by nutritional stress (Hobson and Clark 1992; Hobson et al. 1993; Mekota et al. 2006; Mekota et al. 2009; Oelbermann and Scheu 2002; Voight and Matt 2004), disease or trauma (Katzenberg and Lovell 1999; Olsen 2013; Petzke et al. 2006; White and Armelagos 1997; Williams 2008), and pregnancy (Fuller et al. 2004). Positive nitrogen balances cause δ^{15}N values to decrease, whereas negative nitrogen balances (caused by catabolic processes) result in increased δ^{15}N values. These complicating factors do not mean that nitrogen isotopic compositions cannot be used to study diet, only that these factors all need to be considered when interpreting δ^{15}N values.

2.6   Maya Food Web

As discussed above, to interpret human paleodiet isotopic data for a region, it is essential to know the carbon and nitrogen isotopic compositions of plants and animals from that area. In order to aid in Lamanai's paleodiet interpretations, a model of the δ^{13}C and δ^{15}N values of potential ancient food resources was constructed using data obtained from past studies (Fig. 2.6-1).

Since maize was the only major C_4 plant that would have contributed to Maya diet, this model only includes maize isotopic compositions, despite the larger global range of C_4 plants. The maize carbon and nitrogen isotopic compositions were obtained from both ancient and modern samples from North and South America (Keegan and DeNiro 1988; Schwarcz et al. 1985; Tieszen and Fagre 1993a; van der Merwe et al. 2000; White and Schwarcz 1989; Williams 2000; Wright 1994). The isotopic compositions of C_3 plants used in the model are derived more locally, with modern samples from Guatemala, Belize, and the Caribbean (Keegan and DeNiro 1988; White, Pohl, et al. 2001; Wright

1994). This is also true of the terrestrial animals (including herbivores, omnivores, and carnivores), which are from the Pasión region of Guatemala and several sites in Belize, including Lamanai itself (Tykot et al. 1996; van der Merwe et al. 2000; White and Schwarcz 1989; White, Pohl, et al. 2001; Williams 2000; Wright 1994). The δ^{13}C and δ^{15}N values of marine fish, marine invertebrates, and reef/estuary fish come from coastal Belizean and Caribbean samples (Keegan and DeNiro 1988; Tykot et al. 1996; Williams
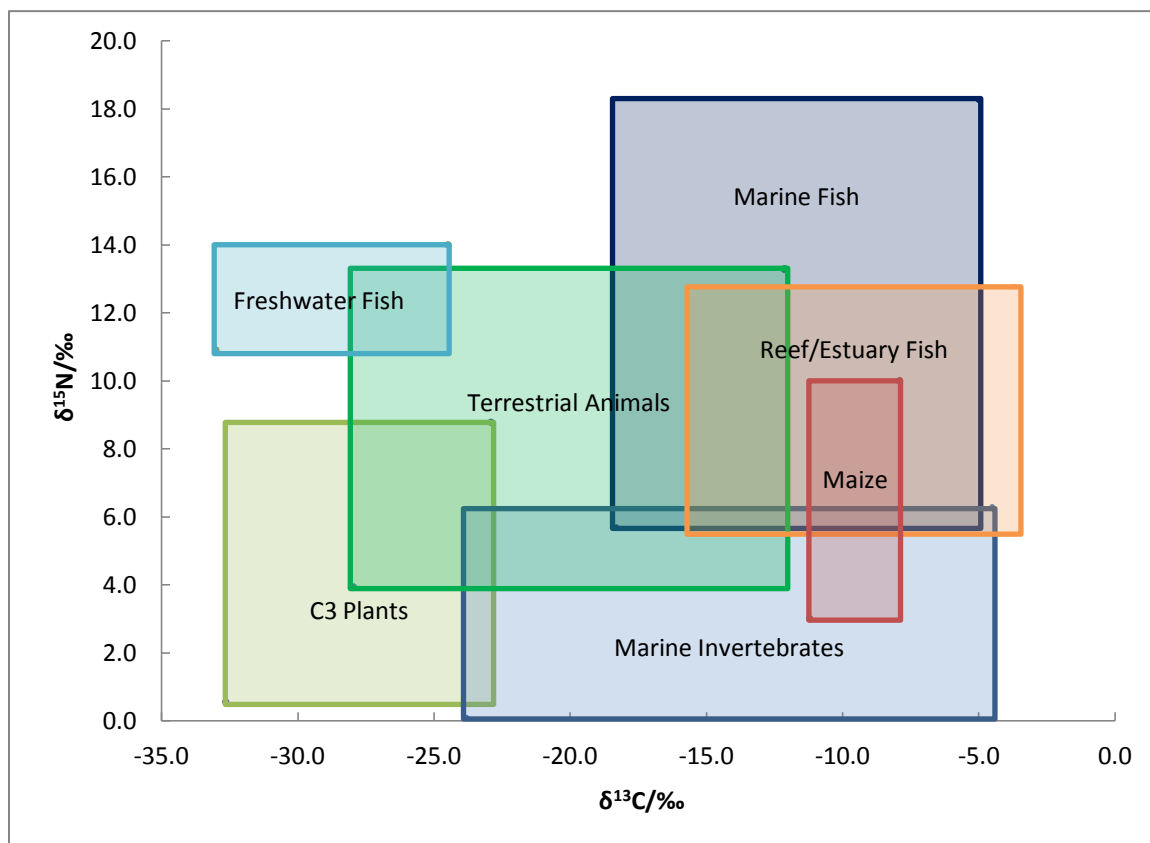
Figure 2.6-1 The ranges of stable carbon- and nitrogen-isotope ratios of foods that may have been available to the ancient Maya at Lamanai. Data were obtained from modern and ancient floral and faunal samples (Keegan and DeNiro 1988; Schwarcz et al. 1985; Tieszen and Fagre 1993a; van der Merwe et al. 2000; White and Schwarcz 1989; White et al. 2001; Williams 2000; Williams et al. 2009; Wright 1994).

2000; Williams et al. 2009), while freshwater fish isotopic compositions come from only a few modern Guatemalan samples[8] (Wright 1994).

In order to represent the $\delta^{13}C$ and $\delta^{15}N$ values in the Maya food web model for past diets (Fig. 2.6-1), some adjustments to the isotopic compositions obtained from the previously published studies were made. The isotopic compositions of the fish, shellfish, and terrestrial animals shown in Figure 2.6-1 represent meat δ-values (as meat was the tissue most likely being consumed). However, many of the isotopic compositions originally reported, particularly of archaeological specimens, were for more durable materials, such as collagen. Accordingly, the $\delta^{15}N$ values of all collagen samples were adjusted upwards by 1.7 ‰ to represent meat[9] (Keegan and DeNiro 1988). For the carbon isotopic data, the situation was slightly more complicated. The archaeological collagen $\delta^{13}C$ values were all adjusted downward by 3.7 ‰ to represent meat isotopic compositions, whereas the modern collagen was only adjusted downwards by 2.2 ‰ (Keegan and DeNiro 1988). This difference of 1.5 ‰ accounts for the Suess effect, which arises from the burning of fossil fuels in modern times (refer to section 2.4 for a more detailed explanation). In other words, all modern, non-marine carbon isotopic compositions were adjusted upwards by 1.5 ‰ to account for the Suess effect. The Suess effect on marine $\delta^{13}C$ values appears to be lagging behind the atmospheric effect, as surface waters mix with deeper, older ocean waters. Based on recent literature on this "Oceanic Suess effect", there has yet to be consensus on appropriate adjustments (e.g., Katzenberg et al. 2012; Lee-Thorp 2008; Misarti et al. 2009; Newsome et al. 2004; Racapé et al. 2013; Robson et al. 2012; Swart et al. 2010; Szpak, Orchard, et al. 2012), therefore none was applied to the marine $\delta^{13}C$ values in Figure 2.6-1.

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[8] There is a recent isotopic study of modern freshwater fish in southern Belize by Winemiller et al. 2011; however, due to a number of considerations (e.g. ecosystem differences), data from this study were not included.

[9] When consumed food is transformed into tissues in the consumer's body its isotopic composition can undergo fractionation, which results in differences not only between diet and consumer, but differences among different tissues within a consumer.

2.7   Diagenesis

After death, bones and teeth undergo histological, chemical, and mineralogical changes. These alterations include changes in porosity, the degradation and loss of collagen, the uptake of cations and circulating organics, exchange of ions, and infilling with mineral deposits, as well as the alteration, and even dissolution, of the mineral matrix (e.g., Collins et al. 2002, Hedges 2002). These post-mortem alterations are individually and collectively referred to as diagenesis. Diagenesis is a very complex, site-specific process that is not linearly related to burial time, and is affected by a multitude of factors including temperature, humidity, hydrology, pH, redox conditions of the burial environment, and microbial attack (e.g., Berna et al. 2004; Bocherens et al. 2008; Hedges 2002; Hedges and Millard 1995; Hedges et al. 1995; Person et al. 1995; Wang and Cerling 1994). This variability makes diagenetic change a very complex issue. Attempts to understand diagenesis in the context of archaeological (and paleontological) skeletal tissues have been summarized in several reviews and special issues of journals (e.g., Hedges 2002, Lee-Thorp and Sealy 2008; Tütken and Venneman 2011). Part of the reason that understanding diagenesis is so important is that without undergoing some chemical change, few bones and teeth would survive to enter the archaeological and fossil records (Lee-Thorp and Sealy 2008). However, in order to use these skeletal tissues to make interpretations about the past, researchers depend on the preservation of the original biogenic information (e.g., stable isotope compositions). Thus, the study of diagenesis is necessary to establish how much alteration has taken place and to what extent it affects the information of interest to the researchers.

As discussed in section 2.2, although bones and teeth are similar, there are important differences. These differences are a factor in the susceptibility of each tissue to diagenesis. Bone has a high organic content, high porosity, and low crystallinity[10] (LeGeros 1991). These characteristics, along with a high degree of elemental substitution that tends to increase solubility and reactivity of bone bioapatite (Dorozhkin 2009), make

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[10] "The term crystallinity denotes both size and perfection of crystal; in other words, poor crystallinity implies both internal distortion and small crystal size" (Lee-Thorp 2008:930).

it susceptible to a variety of diagenetic processes (as will be discussed below). Compared to bone, tooth enamel is more resistant to diagenetic changes due to its smaller organic component (<1%) and less heavily substituted bioapatite, as well as its larger crystals and minimal porosity (giving less surface area for exchange or reactions to take place) (LeGeros 1991; Dorozkhkin 2009). The preservation of original isotopic compositions in enamel, even on a geological timescale, has been reported in numerous studies (e.g., Lee-Thorp and Sponheimer 2003; Tütken et al. 2008), and enamel has frequently been demonstrated to retain its original isotopic composition for longer and under less ideal conditions than other skeletal tissues (e.g., Ayliffe et al. 1994; Sharp et al. 2000; Tütken et al. 2008). However, enamel can still undergo alteration (e.g., Schoeninger et al. 2003), particularly due to bacterial processes (Zazzo, Lécuyer, and André 2004; Zazzo, Lécuyer, and Mariotti 2004).

As bone is more susceptible to diagenesis than enamel, it will be the focus of the following discussions[11]. Four diagenetic parameters for the description, identification, and categorization of bone diagenesis were proposed by Hedges et al. (1995) and Nielsen-Marsh and Hedges (2000). These parameters are histological preservation, porosity, protein (or collagen) content, and crystallinity. Although the direct relationships among each of these four parameters and diagenesis are still not completely understood (Hedges 2002; Lee-Thorp and Sealy 2008), these indicators are still useful when discussing the mechanisms of and the factors affecting diagenesis.

2.7.1   Diagenetic Processes

Diagenetic processes are set in motion and alteration can start quickly after death, even before burial (Bell et al. 1996; Fernández-Jalvo et al. 2010; Trueman et al. 2004; Tuross et al. 1989). Although diagenesis is site-dependent, there are a few general diagenetic "pathways" or "mechanisms of change" that have been identified (Collins et al. 2002; Smith et al. 2007). Drawing from Collins et al. (2002) and Smith et al. (2007), they are: chemical deterioration of the organic phase, chemical alteration of the mineral phase, and

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[11] This is not to say that that the processes to be discussed cannot affect enamel, as they can; particularly relevant are discussions of microbial attack.

microbiological attack. In the following sections, each of these diagenetic pathways will be discussed individually before moving on to a discussion of their interaction with each other and some influencing environmental factors.

2.7.1.1   Deterioration of the Organic Phase

About 20–30% of bone is organic and, of that, approximately 90% by weight is collagen. Even though the organic portion of bone has a shorter "shelf-life" than the inorganic component (as it dissolves and denatures quickly on a geologic time scale), under ideal conditions measurable amounts of collagen can survive for more than 100,000 years (e.g., Jones et al. 2001). The loss of the organic phase can be caused either by slow, long-term degradation or accelerated deterioration as a result of pre-depositional treatment and/or the burial environment (Collins et al. 2002).   The rate of collagen loss is dependent on time, temperature, site hydrology, and environmental pH, with factors such as high temperatures and alkali soils accelerating loss (Collins et al. 2002; Hedges 2002; Rudakova and Zaikob 1987). Accelerated chemical deterioration of just the organic phase is relatively unusual and only occurs in environments that are geochemically stable for bone mineral (Collins et al. 2002). In this case, histology is a poor indicator of collagen content since the histology of an affected bone can appear relatively well-preserved (Hedges et al. 1995; Kolodny et al. 1996; Smith et al. 2007). In fact, a loss of collagen in conjunction with collagen's replacement by minerals is one of the key mechanisms leading to the preservation and fossilization of bones (Collins et al. 2002; Smith et al. 2007). Increases in mineral crystallinity are often observed in conjunction with the loss of the organic phase (e.g., Nielsen-Marsh and Hedges 2000; Person et al. 1995; Smith et al. 2007).

Degradation of collagen does not necessarily mean alteration of the biogenic isotopic compositions (van Klinken 1999). As it is breaking down, collagen generally preserves its bulk isotopic integrity (δ^{13}C and δ^{15}N), amino acid composition, and C:N ratio until more than 99% of a bone's collagen has been lost (Dobberstein et al. 2009). Therefore, it is likely that as long as a sample yields enough collagen to perform stable isotopic analysis, the obtained results will not be affected by diagenetic change.

2.7.1.2   Alteration of the Mineral Phase

As highlighted by Lee-Thorp and Sealy (2008), diagenesis in bioapatite can progress along several pathways: (i) dissolution eventually leading to complete disappearance (particularly when pH conditions are not ideal) (Berna et al. 2004); (ii) recrystallization; (iii) the addition of exogenous mineral material into interstitial spaces; and (iv) ionic and isotopic exchange. Each of these will briefly be discussed in turn. While these changes are relevant to bioapatites in general, bone is particularly susceptible to these changes, with enamel being relatively resistant.

Dissolution is highly dependent on soil chemistry and hydrology (Hedges and Millard 1995). In neutral pH soils with calcium and phosphate concentrations close to saturation in relation to bioapatite, the dissolution rate is very slow. However, in conditions where the burial environment is greatly under-saturated (e.g., pH reduction or recharge with fresh water), dissolution can occur rapidly (Hedges 2002). Hedges and Millard's (1995) bone mineral loss model is controlled by diffusion, which suggests that the rate of loss would be proportional to the exposed surface area. Dissolution increases the porosity of the bone, and, in turn, increased porosity accelerates the rate of dissolution. Even though dissolution can lead to the complete loss of the skeletal material from the archaeological record, in some cases the dissolved material can be reprecipitated.

Under ideal conditions for survival (e.g., near neutral pH), the post-mortem trend for bioapatites is towards greater stability as a result of recrystallization and crystal growth (or Ostwald ripening). With this recrystallization the crystals become larger and more ordered, which results in an increase in crystallinity. This can occur relatively quickly after death (Berna et al. 2004; Trueman et al. 2004; Tuross et al. 1989) and without environmental promoters (Person et al. 1995)[12]. As a result of the reactivity of bone bioapatite, it is vulnerable in early stages to the dissolution/recrystallization process, but once its crystallinity has increased, it becomes more resistant (Lee-Thorp 2002). Selective dissolution of more soluble, less ordered crystals may also occur (Wright and

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[12] In contrast, changes to enamel are often minimal, even after a long time (Ayliffe et al. 1994).

Schwarcz 1996), but relative to recrystallization, such a process is thought to play only a minor role in observed crystallinity changes (Brock et al. 2010). As recrystallization can be the result of internal rearrangements, the original isotope composition may not necessarily be altered (Lee-Thorp 2008). However, the dissolution, reprecipitation, and recrystallization of bioapatite can alter its isotopic composition due to non-equilibrium isotope fractionation (Stuart-Williams et al. 1996)[13]. Recrystallization can also result in the loss of the original ions and incorporation of foreign ions into the crystal structure, which can cause its original isotopic composition to be changed.

During diagenesis, there is the opportunity for intense chemical and isotopic exchange between the bioapatite and the surrounding environment that can result in the addition of exogenous material through processes such as diffusion, ion exchange in the bioapatite structure, adsorption of ions, or by the precipitation of secondary minerals in pore spaces (e.g., Hedges 2002; Hedges and Millard 1995; Kohn et al. 1999; Kolodny et al. 1996; Lee-Thorp 2002; Trueman et al. 2004). Some of these changes can affect crystallinity, such as the uptake of fluoride (F^-) or carbonate (CO_3^-). Others can affect the rate of continued diagenesis by affecting solubility (e.g., incorporation of F^- into the mineral structure stabilizes the bioapatite, whereas CO_3^- makes it more soluble) or porosity (e.g., precipitation of secondary minerals in the pore spaces reduces porosity and ultimately slows the rate of diagenesis). In addition, the incorporation of exogenous material or exchange with the burial environment can also affect isotopic results (e.g., altered carbon isotopic signals in bioapatite due to exchange of CO_3^- with ground or soil water – Wright and Schwarcz 1996). These types of changes to bioapatite, as well as recrystallization and dissolution, can all potentially have varying levels of impact on a sample of bone or enamel throughout its post-mortem history.

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[13] Non-equilibrium fractionation, in contrast to equilibrium fractionation, describes situations where the reaction is dominantly a forward reaction with little or no back reaction (either due to the type of reaction or the process of an equilibrium reaction cut short). An example of this directly applicable here would be if some of the bone mineral had been dissolved into soil water, and then a flushing event occurred (e.g. a flood), ensuring that those original ions could not all be reincorporated or reprecipitated into the bone.

2.7.1.3 Microbial Attack

Microbial attack by bacteria, fungi and/or non-vascular plants can begin fairly rapidly, and results in tunneling and destruction that can cause both collagen and mineral loss, as well as redistribution of bone material (Bell et al. 1996; Child 1995; Fernández-Jalvo et al. 2010; Hedges et al. 1995; Jans 2008; Jans et al. 2004). Microbial attack often starts with initial demineralization of the bioapatite caused by microbially-produced enzymes and acids (Bell et al. 1996; Child 1995; Collins et al. 2002; Jans 2008). This dissolution of the mineral phase allows the microbes access to the collagen, which would have otherwise been protected by the bioapatite (Collins et al. 2002; Jans 2008). Although the diagenetic changes precipitated by microbial attack are similar to the changes caused by chemical alteration (e.g., collagen loss, dissolution, recrystallization, etc.), the damage of a microbial attack is more localized (Brady et al. 2008; Collins et al. 2002). This alteration to the bone mineral and the loss of collagen increases porosity, and these changes can accelerate further diagenesis (Hedges 2002; Smith et al. 2007). The result of all these concomitant diagenetic changes is that crystallinity also generally increases with the degree of microbial attack (Smith et al. 2007).

Conditions of the burial environment that favour microbial growth (e.g., near neutral pH, a certain level of humidity for fungi, the presence of light for cyanobacteria, etc.) increase the likelihood of attack, as does the state of the bones before they enter the ground. Jans et al. (2004) have demonstrated that bacterial alteration is more than twice as common in human bone as in animal bone at archaeological sites. They suggest that this is related to the condition of bones before burial as animal bones are often prepared for food, and human burial practices often involve interment of a fleshed body. Although a fleshed body may be more appealing to bacteria, as defleshed animal bones are not affected by putrefaction, they more frequently experience fungal attacks (Jans et al. 2004).

As with chemically-induced diagenetic changes, microbial attack can also change biogenic isotopic compositions. In fact, in some cases they can have a greater impact, particularly on materials that were resistant to other forms of diagenetic change. For example, there is some evidence to suggest that bacteria can preferentially affect certain collagen amino acids, which would modify bulk collagen δ^{13}C and δ^{15}N values (Balzer et

al. 1997; Child 1995; Grupe et al. 2000; Harbeck and Grupe 2009). In addition, although phosphate-oxygen in bioapatite is understood to be fairly resistant to diagenetic change, there is significant evidence to suggest that diagenesis due to microbial activity modifies $\delta^{18}O_p$ – even in enamel (Ayliffe et al. 1994; Blake et al, 1997; Kolodny et al. 1996; Longinelli 1996; Sharp et al. 2000; Zazzo, Lécuyer, and André 2004; Zazzo, Lécuyer, and Mariotti 2004).

2.7.1.4 Interactions

While each of these pathways result in particular diagenetic changes, they also interact and affect one another. For example, Smith et al. (2007) have suggested that certain processes actually prevent other processes from occurring, as they found that in bone, microbial attack and accelerated collagen hydrolysis[14] are mutually exclusive. It also seems that changes in the organic and inorganic portions of bone influence diagenetic change in each other.

The presence of collagen can significantly affect the stability of the mineral matrix (Hedges 2002). Whether chemically-mediated or a result of biological attack, the loss of collagen affects bone's porosity (Nielsen-Marsh and Hedges 2000). As collagen is lost, it exposes the reactive surfaces of the thermodynamically unstable bioapatite crystals, thus increasing their susceptibility to dissolution and structural alteration (e.g., Nielsen-Marsh and Hedges 2000; Trueman et al. 2004). However, collagen dissolution also provides pore space for the deposition of exogenous minerals (e.g., Olesiak et al. 2010), which, as discussed above, ultimately slows down a sample's deterioration[15].

As collagen protects the mineral portion, the bioapatite returns the favor. The interlacing of bone bioapatite crystals with collagen fibrils slows its breakdown and buffers against low pH soils (Collins et al. 1995; Collins et al. 2002; Kronick and Cooke 1996). When the mineral portion deteriorates, this protection is no longer provided to the

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[14] Accelerated collagen hydrolysis is the rapid, apparently chemically-mediated, loss of collagen.

[15] Although it does slow down a sample's deterioration, the deposition of exogenous minerals does increase the risk of obtaining altered isotopic compositions, especially for structural carbonate (unless pretreatment for secondary carbonates is done effectively).

collagen. The chemical dissolution of the bioapatite will also expose organic material to microbial attack and will allow the increased participation of water, which can accelerate the breakdown of the organic component (Collins et al. 2002). In ways such as these, diagenetic processes influence each other, furthering the preservation or deterioration of skeletal remains.

2.7.1.5   Environmental Factors

The burial environment is one of the most important factors in determining the preservation potential of bone. Although there are many aspects of the environment that play a role in influencing diagenesis (some of which were noted above), there are three key factors: temperature, geochemistry, and hydrology. Temperature can act to either promote or inhibit diagenetic change. For example, high temperatures accelerate the rate of collagen loss (Collins et al. 2002; Hedges 2002), whereas very low temperatures can inhibit microbial attack (Hedges 2002).

Geochemistry of the burial environment includes elements such as solute concentrations, redox potential, and pH. The solute concentration and redox potential in the burial environment affects both the rate of uptake of exogenous material (e.g., secondary carbonates) and the loss of endogenous bone material (i.e., dissolution of bone mineral or degradation of collagen), as well as ionic and isotopic exchange. In general, chemical deterioration is accelerated at pH extremes; however, for microbial attack, a neutral pH is optimal (Collins et al. 2002). The geochemistry of a burial environment is often closely related to its hydrology.

Site hydrology is one of the strongest influences on the outcome of bone preservation (Hedges and Millard 1995; Nielsen-Marsh and Hedges 2000). There are three ways in which water (and its solutes) interact with skeletal remains: diffusion, hydraulic flow, and recharge (Hedges and Millard 1995). All three of these can occur together, but their impact on diagenesis depends on how much the pore structure has already been altered by diagenesis and what kind of chemical change is taking place (Hedges and Millard 1995). The changes influenced by hydrology include the uptake of exogenous material into the bone (e.g., cations, anions, and/or organics), porosity development due to the removal of

endogenous material (e.g., dissolution of bone apatite or deterioration of collagen), and recrystallization (Hedges and Millard 1995). Hydrology also impacts microbial attack, as it is more common in well-drained soils and both dry and very wet (anoxic) environments can inhibit microbial attack (Hedges 2002). It is clear that temperature, geochemistry, and hydrology can all have important impacts on diagenesis.

2.7.2   Methods of Detection

Since diagenetic changes can mean an alteration of the original isotopic composition, it is important to select samples carefully and attempt to determine the extent of diagenetic change. While studies have used many different techniques to characterize and evaluate the extent of diagenetic change, two of the most widely and routinely used methods to assess the suitability of material for isotopic analysis are the examination of a standard suite of collagen quality characteristics and the application of Fourier Transform Infrared Spectroscopy (FTIR) to appraise the integrity of bioapatite.

2.7.2.1   Evaluating Collagen

The standard set of measures used to evaluate the suitability of collagen for isotopic analysis are collagen yield, weight percent of carbon (C) and nitrogen (N), and atomic C:N ratios (Ambrose 1990; van Klinken 1999). These approaches are commonly used by both the stable isotope community and most radiocarbon laboratories. Although no one test can provide a definitive answer on the state of collagen preservation, taken together, they provide a significant amount of information about the amount of collagen and its elemental characteristics. These measures are used to evaluate how much the collagen of archaeological samples has changed from that typical of modern material. Since collagen generally preserves its bulk isotopic composition (δ^{13}C and δ^{15}N), amino acid composition, and C:N ratio until almost all of a bone's collagen is lost (Dobberstein et al. 2009; van Klinken 1999), the biogenic isotopic composition of collagen is likely to be retained so long as the collagen yield is ≥1% weight. A further check is provided by comparison of the atomic C:N ratio and the weight percent C and N contents of archaeological collagen to modern bone. This evaluation ensures awareness of preferential loss of certain amino acids that may affect isotopic compositions. These

measures have become the "gold standard" for assessing collagen preservation over the last three decades (Pestle and Colvard 2012).

2.7.2.2   FTIR

One of the most common methods to assess the degree of diagenetic alteration of bioapatite is Fourier Transform Infrared Spectroscopy (FTIR). (For detailed methodology see section 4.4). The spectrum produced reveals the molecular composition of the sample. A crystallinity index (CI) for the bioapatite crystals can be calculated from the spectrum, which describes their size and structural order. Since unaltered bone bioapatite crystals are generally small and less ordered (Sillen 1989), high CI values can indicate post-mortem alteration (because, as discussed above, recrystallization of bioapatite during diagenesis can cause the crystals to become larger and more highly ordered). However, high crystallinity does not always correlate to a diagenetic change, or at least a diagenetic change that has affected the original isotopic compositions. It has been demonstrated that even in cases where the CI indicates alteration, phosphate-oxygen isotopic compositions were still preserved (Stuart-Williams et al. 1996). Conversely, even if the CI falls within the accepted range, isotopically significant alteration may still have occurred (Trueman et al. 2008).

The carbonate content of bioapatite can also be estimated from the FTIR spectrum by using the carbonate to phosphate (C/P) ratio, calculated using their corresponding peak absorbances (the carbonate peak at 1415 cm^{-1} and the phosphate peak at 1035 cm^{-1} – see section 4.4 for a full description).   In bioapatite, carbonate substitutes for phosphate so the proportions of the two ionic complexes should vary inversely. Low C/P ratios relative to modern bone can be caused by carbonate loss due to bioapatite dissolution or recrystallization, whereas elevated ratios can indicate the adsorption or incorporation of exogenous carbonate into the mineral structure (Nielsen-Marsh and Hedges 2000).

The presence of exogenous minerals that are common indicators of post-mortem alteration can also be identified using FTIR. Calcite, in particular, is a secondary mineral that can precipitate onto and into bioapatite during diagenesis (e.g., Lee-Thorp and van der Merwe 1991; Roche et al. 2010). Likewise, the incorporation of F into the mineral

structure can result in bioapatite conversion to fluorapatite or francolite, which are other indicators of diagenesis. Formation of francolite means that some of the phosphate has been replaced, and in situations where recrystallization to fluorapatite has occurred, it can be accompanied by stable isotopic alteration (Schoeninger et al. 2003).

2.7.2.3 Summary

In sum, stable isotope analysis allows us to access information at the level of the individual, including at different points within a lifetime. Oxygen-isotope analysis can be used to study the residential history of an individual or mobility in groups. Carbon- and nitrogen-isotope analysis can be combined to provide information on paleodiet, which can be used in some cases to support the identification of non-local individuals (if there are dietary differences between sites or regions). With each of these types of isotopic information there are interpretative issues to be considered, in addition to the possibility that the biogenic isotopic compositions may have been altered over time through diagenetic processes.

Chapter 3

3   Lamanai Site and Sample

3.1   Location and Environment

The name "Lamanai" means "submerged crocodile", and it is one of the few original names for Maya sites that are recorded (Pendergast 1981). Technically part of the Southern Maya Lowlands (although often not discussed as such), Lamanai is located in northern Belize (Fig. 3.1-1). The archaeological site of Lamanai is found within the Lamanai Archaeological Reserve, a 3.8 km^2 park protected by the government and located in Belize's Orange Walk District[16]. The site is situated on the northwest bank of the New River Lagoon, next to the modern day village of Indian Church (Fig. 3.1-2).

Belize has a humid tropical climate with a distinct wet season between May and November. Annual precipitation in Belize varies significantly across the country, with the north receiving four times less than the south (Bridgewater 2012). The zone where Lamanai lies generally receives less than 180 cm of rainfall per year (Wright et al. 1959:fig. II). Lamanai is located in a heterogeneous environment with access to good agricultural soils (Lambert et al. 1984) and an abundant supply of fresh water. The site is situated in an area of broadleaf forest, with nearby *bajos* (marsh forest) and areas of pine ridge savannah occurring to the north and to the east (directly across the lagoon). The lagoon and the New River provide access to the resources of riverine, lacustrine, and estuarine environments (e.g., fish, gastropods, and turtles), as well as coastal resources, as Lamanai is located only about 80 km from the Caribbean coast by water (Coyston et al. 1999; Emery 1990; Emery 1999).

Over 718 structures within 4.5 km^2 have been recorded at Lamanai (with the mapping done between 1974 and 1976 under the supervision of H.S. Loten) (Fig. 3.1-3) and just north of this mapped area there is evidence of a raised-field system (Luzzadder-Beach et

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[16] This reserve, created in 1976, acts both as a cultural and a natural reserve focused on research, conservation, and protection of both the site and the natural environment that it encompasses.
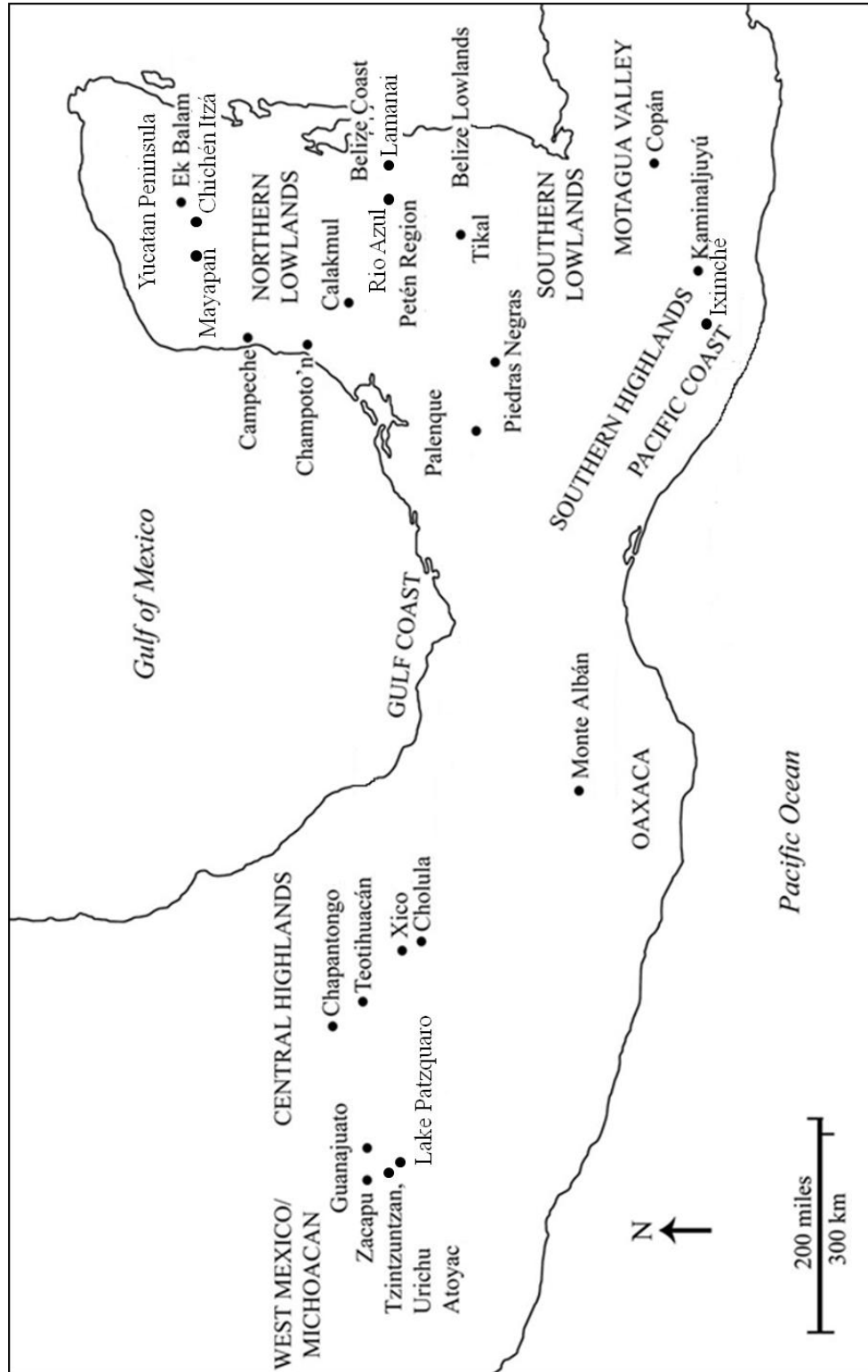
Figure 3.1-1 Map of Mesoamerica (adapted from White et al. 2007)

Figure 3.1-2 Map of Belize (adapted from Graham and Pendergast 1989)

al. 2012; Pendergast 1979, 1981). The site is laid out in a strip along the lagoon. This strip development next to the lagoon's edge is a "decidedly non-standard settlement pattern", as the usual arrangement is one or more ceremonial precinct plaza groups
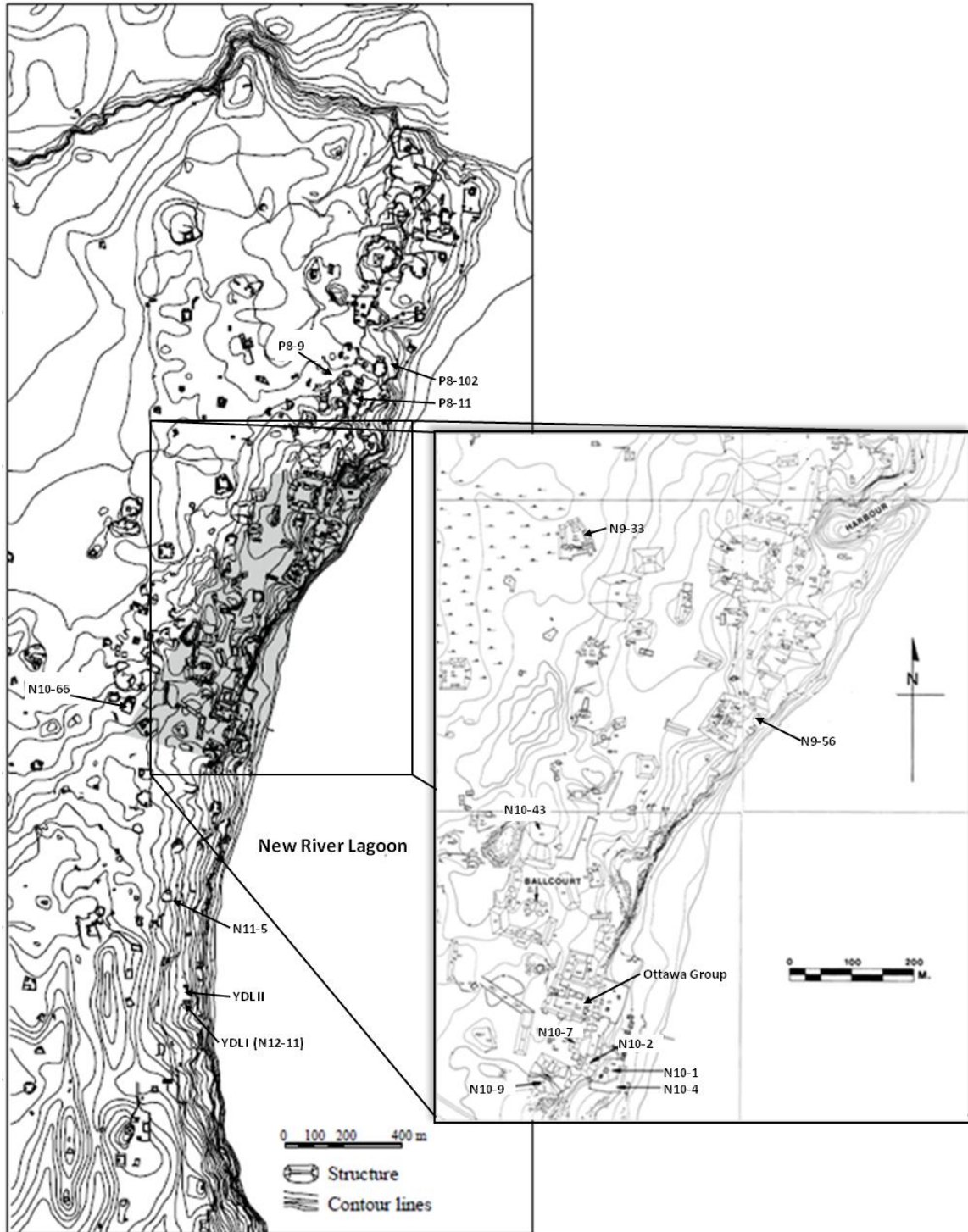
Figure 3.1-3 Lamanai site map (adapted from Howie 2006a; Pendergast 1981)

encircled by residential and other small structures (Pendergast 1981:32). Located as it is on the banks of the New River Lagoon, Lamanai was strategically situated to participate

in both coastal and inland trade routes and lines of communication (Pendergast 1986; Howie 2012). This lagoon-side environment served as the backdrop for a community that survived over two millennia.

3.2 Culture History

Lamanai has a long, rich history, with a continuous occupation of more than 2000 years. Table 3.2-1 and Table 3.2-2 outline Lamanai's time periods with corresponding dates and ceramic phases. In the following sections, the Preclassic, Classic, Terminal Classic, Postclassic, and Historic periods at Lamanai will each be discussed briefly in turn.

Table 3.2-1 Lamanai's Time Periods and Approximate Dates

Time Period	~ Dates
Historic	**AD 1492 to 1700**
Late Spanish Colonial Period	AD 1641 to 1700
Middle Spanish Colonial Period	AD 1544 to 1641
Early Spanish Colonial Period	AD 1492 to 1544
Postclassic	**AD 950/1000 to 1492**
Late Postclassic	AD 1350 to 1492
Middle Postclassic	AD 1200/1250 to 1350
Early Postclassic	AD 950/1000 to 1200/1250
Classic	**AD 300 to 950/1000**
Terminal Classic	AD 800 to 950/1000
Late Classic	AD 600 to 800
Early Classic	AD 300 to 600
Preclassic	**pre-AD 300**
Protoclassic	AD 1 to 300
Late Preclassic	300 BC to AD 1
Middle Preclassic	1000 BC to 300 BC
Early Preclassic	? to 1000 BC

Source: Graham 2008a; Graham, personal communication; Powis 2002.

3.2.1 Preclassic

The first evidence of occupation dates to 1500 BC with the discovery of offering activity in the "harbour"[17] in the northern area of the site (Pendergast 1998:56). However, it is not until the Middle Preclassic that significant evidence of occupation has been uncovered, with evidence of habitation in the northern section of the site and Structures

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[17] Although this area was originally hypothesized to be a harbour (Pendergast 1981, 1998), more recent research has demonstrated that geologically this was not possible (Powis et al. 2009).

Table 3.2-2 Lamanai's Ceramic Chronology

Time	Ceramic Complex
1500	YGLESIAS
1400	CIB
1300	
1200	BUK
1100	
1000	
900	TERCLERP
800	
700	TZUNUN
600	SHEL
500	
400	SAC
300	
200	
100	ZOTZ
A.D. 1/ B.C. 1	
100	
200	LAG
300	
400	
500	
600	MESH
700	
800	
900	
1000	

Source: Modified from Howie 2012; Powis 2002.

P8-9, P8-11, P8-103, N9-56, and N10-43 securely dated to this period (Pendergast 1980a, 1981; Powis 2002:54).

Structure N10-43, which is part of Lamanai's central precinct, is 33 m high and is thus one of the largest securely dated Preclassic buildings in the Maya area. The magnitude of this construction has obvious implications for the understanding of Lamanai's importance in the lowlands during the Preclassic period, since it is clearly the result of labour drawn from a large established community controlled by a powerful group of elites (Pendergast 1981).

Structure N9-56 is another example of a ceremonial construction whose original phase dates to the Preclassic period. While its existence reinforces Lamanai's establishment as a large center, it is also interesting because it provides evidence of Lamanai's links to the region at large. A plasterwork mask found in association with the Preclassic structure closely resembles those found at the site of Cerros (located approximately 80 km NE of Lamanai in the Corozal District of Belize). The similarities among these architectural embellishments are great enough to suggest close contact between architects in the two sites[18] (Pendergast 1981:42).

Overall, the architecture of Preclassic Lamanai is characterized by a diversity of forms; however, other aspects of its material culture displayed a certain amount of rigidity, such as the nature of offerings as well as the surface decoration and form of ceramics[19] (Pendergast 1981:42; Powis 2002). Lamanai's Late Preclassic ceramic sequence is closely linked to other sites in northern Belize and beyond, all of which participated in the 'Chicanel Ceramic Sphere' (Powis 2002). These links to other sites extend beyond a sharing of ideas and techniques to the sharing of goods, as there is also evidence of

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[18] It has been suggested that the transformation of Cerros from a "village into a small regal center" could have been due to outside influences, and it is possible that Lamanai, as the nearest major Preclassic centre, could have been this influence (Sharer 1994:118-120).

[19] Examination of the ceramic inventory also reveals that during the Late Preclassic and Terminal Preclassic periods, both elites and commoners had access to fine quality pottery, as well as to a wide range of utilitarian wares (Powis 2002). It was not until the Early Classic that differences in access to fine wares appeared, reflecting a growing social inequality (Graham 2004:226).

imported ceramics at Lamanai (including those possibly made at or near Altun Ha) (Powis 2002; Powis et al. 2006). Evidence of trade is also found in non-ceramic items, such as objects of marine shell, granite, obsidian, and jade (Pendergast 1981; Powis 2002). This evidence of interaction and trade, combined with the architectural evidence (both residential and ceremonial), clearly demonstrates an extensive, well-developed, and well-connected occupation at Lamanai by 300 BC, which set the stage for Lamanai's continued growth in the Classic period.

3.2.2   Classic

Although during the Classic period Lamanai was "peripheral" to the southern Maya lowlands (the Central Petén is often viewed as a "core" area during the Classic), it experienced a similar Classic period cultural florescence, which is evident in the numerous building projects and enhancement of its Preclassic status. One example of these building projects was the monumental construction of Structure N10-9, colloquially referred to as to as the "Jaguar Temple" as a result of the Olmecoid jaguar masks on the basal platform (Pendergast 1978). The Early Classic also saw the beginnings of the elite residential and administrative plaza group N10-3 or the "Ottawa" complex, which subsequently underwent many changes throughout its lifetime that extended through the Late Classic into the Postclassic period (Graham 2004).

There is still much that is unknown about Lamanai's Late Classic period (Graham 2004). However, there is strong evidence of heavy control in architecture, and possibly other aspects of life, particularly during the beginning of this period (Pendergast 1981:42). For example, it was during the Late Classic that the first evidence of the building pattern now known as the *Lamanai Building Type* appeared. The Lamanai Building Type refers to "the presence of a chambered building set across the center stair of a terraced platform with no building at the structure summit present" (Powis 2002:55), and has been identified in the Late Classic modifications to Structure N10-9, as well as elsewhere at Lamanai (e.g., Late Classic modifications of N9-56) (Pendergast 1981). It is also found at the neighbouring community of Altun Ha (~ 40 km east) and may be characteristic of several other central Lowlands sites (Pendergast 1981). As the Classic period drew to a close, sites all over the Maya world (including near neighbours, like Altun Ha)

experienced decline and 'collapse'; Lamanai, however, continued on into the Postclassic period.

3.2.3 Terminal Classic

During the Terminal Classic, a period of transition from the Classic to the Early Postclassic, the northern lowland states (such as Chichen Itza) expanded and migration was motivated by instability and ongoing conflict in both the southern and northern lowlands. At the same time, exchange, communication, and political networks and affiliations were disrupted by the decline and 'collapse' of the institutions of power in the Central Petén and surrounding areas, and new trade systems emerged. The Terminal Classic period at Lamanai offers interesting insights into the effects of regional developments on the local level, because of its central location between the declining sphere of power in the southern lowlands and the rising powers in the Yucatan to the north (Howie 2006a, 2006b). There is evidence to suggest that during this time of political turmoil and change, Lamanai may have been accepting displaced persons (Howie 2006a, 2006b, 2012; Howie et al. 2010), as it was still a thriving community engaged in both building projects and trade.

Evidence of this continued prosperity during the Terminal Classic is seen in the construction of Lamanai's lone ballcourt in front of N10-43. The north-south oriented ballcourt is very small in size and has a massive marker disc in the middle of the playing field. Beneath this marker is a cache that housed a Terminal Classic-style lidded vessel containing two miniature vessels, small objects of jade and shell, some cinnabar, and 9.7 cm^3 of liquid mercury (Pendergast 1980d, 1981:40, 1982a, 1986b:229-230). Although the ballcourt itself is very reminiscent of Structure 61 at Cerros (Powis 2002:59; Scarborough 1985:336), the presence of the mercury suggests links between Lamanai and Copan or other sites in western Honduras, as Honduras is the likely source of the metal (Pendergast 1982a, 1986b).[20] Not only does the ballcourt suggest links with other urban centers located a considerable geographic distance away, but demonstrates that while

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[20] This is the first reported occurrence of mercury in the Maya Lowlands (Pendergast 1980c, 1982a).

building activities were ceasing at other major centers, the community at Lamanai continued to invest time and effort into completing large scale construction projects (Pendergast 1980c, 1986b:230).

3.2.4   Postclassic

Lamanai entered the Postclassic period as a prosperous community. In fact, despite previous understandings of the Postclassic Maya world as a time of depopulation and social, economic, and political decay, Lamanai maintained its vibrancy and continued to grow, as demonstrated by the expansion of the settlement southward (Howie 2006a, 2012; Pendergast 1981, 1982c). Lamanai's proximity to the lagoon provided access to a variety of resources, offering its citizens a rich and varied diet, especially when combined with the products of its raised field agriculture. Evidence from isotopic analysis and dental pathology indicates that the site's population was in good health during the transition, enjoying a mixed diet that becomes dominantly maize-based during the Postclassic (White 1997). The stability of its resources was likely not the only factor in Lamanai's survival. In addition to resource provision, the lagoon may have also provided social stability by providing an access route and a line of communication to northern Yucatan, and ultimately many other parts of Mesoamerica. While these practical reasons may have contributed to Lamanai's prosperity and longevity, it has been suggested that there must have also been some "personal qualities of Lamanai's leaders", efforts to promote solidarity/ease tensions, and/or effective governance strategies that allowed Lamanai to not only survive while other sites fell, but also to thrive (Andres and Graham 2006; Graham 2006; Howie 2006a, 2006b, 2012; Pendergast 1980b, 1986b, 1992).

The main theme that emerges from this discussion of Lamanai's transition from the Classic to the Postclassic period is the duality of continuity and change. Howie (2012:29) succinctly outlines this duality seen in Lamanai's construction activities, architecture, and community space organization and use, as well as in rituals and ceremonial practice. Some of the changes in the material culture suggest that the Early Postclassic elite had different priorities from those of the Classic period rulers; however, the society's organization, at least its key aspects, remained constant (Graham 2004).

Graham (2004) suggests that these priority shifts may have been due to an influx of immigrants or as a result of new alliances.

Continuity and stability is seen in the organization of ceramic production and continued local production of subsistence products, such as maize (Howie 2006a, 2006b, 2012). Although there may have been disruptions and shifts in the exchange networks as a result of Terminal Classic events, it appears that they did not have a noticeably negative effect on local economic patterns (Howie 2006b, 2012).

Throughout the Postclassic period (as is true all through Lamanai's history), there is significant evidence of trade and interaction between Lamanai and the wider Maya world. One connection of note exists between Lamanai and the site of Marco Gonzalez, located on the southern tip of Ambergris Cay (~ 182 km from Lamanai by sea). During its apex, the site's material culture, while distinct, did closely resemble that of Early Postclassic Lamanai, demonstrating their close cultural links (Graham 2011; Graham and Pendergast 1989). For example, the ceramic assemblage at Marco Gonzalez bears strong similarities to Lamanai's Buk phase (Table 3.2-2) (Graham and Pendergast 1989). Lamanai-related Buk phase pottery has also been found at a number of other Belizean sites, including Altun Ha, Mayflower, Negroman-Tipu, and Barton Ramie (Graham and Pendergast 1989).

Styles and ceramics were also travelling in the other direction as well, with many examples of ceramics that were non-local in appearance and/or were made using non-local materials found at Lamanai (Graham and Pendergast 1989; Howie 2006a, 2006b, 2010, 2012; Howie et al. 2010; Pendergast 1978, 1981). For example, in the Late Postclassic period, Structure N9-56 was witness to one or more large ceremonies where "Mayapan-type figurine censors" or *Chen Mul* censors were smashed and scattered over its front, sides, and back (Pendergast 1978, 1981:51). Howie (2010) determined that the majority of these censors (~ 75%), were not locally made and in fact derive from a variety of manufacturing localities both in Belize and the Yucatan, representing both coastal and inland areas.

During the Postclassic period, there were also architectural linkages to sites in the Yucatan, which can be seen in Structures N10-1, N10-2, N10-4, and N10-7 (Pendergast 1981:44; 1986b:235). In addition, Structures N10-2 and N10-4 have yielded a number of copper objects associated with human remains, and these objects have linkages to another area of Mesoamerica – West Mexico. For example, the copper, "button-like ornaments" from Burial N10-4/28 are found (albeit cast in gold) in Monte Alban's Tomb 7 (identified there as headband ornaments) (Pendergast 1981:48). However, the links are not just stylistic. Based on chemical compositional analyses these, and other, Postclassic copper objects have their origins in West Mexico (Hosler 1994). It is important to note that more copper artifacts have been found at Lamanai than at any other site in the southern Maya Lowlands (Simmons 2006). Although there is no evidence for copper production on-site during the Postclassic, by the Historic period Lamanai was producing its own copper and copper-alloyed objects (Simmons 2006). The gold and copper artifacts, along with the presence of imported ceramics and other goods, support Lamanai's continued role as a powerful community in the Postclassic period, one with widespread linkages to the rest of Mesoamerica (Pendergast 1975a, 1980b, 1981, 1986b, 1991).

3.2.5   Historic

With the arrival of the Europeans (particularly the Spanish), the trajectory of the Maya would be forever changed. Although the initial military effort to take control of the Yucatan Peninsula did not start until AD 1527, there had been a Spanish presence in the area since AD 1511. Religious, political, and economic changes imposed by the Spanish, along with slave raids, violent conquest efforts, and the introduction of new diseases, had a devastating effect on indigenous populations.

Lamanai was still obviously a significant centre by the time the Spanish arrived, as it was designated an *encomienda*[21] in AD 1544 (Jones 1989) and efforts were made to the Christianize the Lamaneros. The most obvious of these efforts are the remains of two Historic period churches, likely initiated by Franciscan missionaries (Graham 2011). It

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[21] This means that Lamanai and its populace came under the "governance" of the Spanish, resulting in tribute and labour obligations.

has been suggested that Lamanai was likely a *visita* mission, which means that it was served by part-time visiting priests, with the everyday religious matters put in the hands of local *maestros* (Graham 1998, 2011; Jones 1989).

The churches are located approximately three quarters of a kilometer south of the principal area of Postclassic ceremonial construction. The first church (YDL[22] I) was built by Spanish priests in AD 1544 or soon after (Graham 2011). It was a simple construction with a thatched roof that was built atop an existing indigenous ceremonial structure, following the practice seen elsewhere in the Americas (Graham 1998, 2011; Pendergast 1991:341), and is almost an exact duplicate of the church that was constructed at the site of Tipu (the site of modern day Negroman in western Belize) (Graham 1991, 2011). The second, larger church (YDL II) was founded in AD 1570, and its size suggests that Lamanai was an important center for Christianized Maya in Belize during the 16th and early 17th centuries (Graham 2008b, 2011; Pendergast 1991).

In general, the Maya of Belize had more autonomy than those Maya in areas with Spanish colonists or intensive economic interests (Graham 2011). This likely contributed to their ability to develop and capitalize on new kinds of long distance trade between zones with minimal to nonexistent Spanish resident population (e.g., Belize, southern Campeche, and Peten Lakes) and the more populated towns of northern Yucatan (Graham 2011; Jones 1989). Riverside Belizean cities, like Lamanai, likely played an important role in this trade and also acted as regional collection centers or way stations for tribute items (Graham 2011; Jones 1981, 1989; Wiewall 2009).

Although Lamanai was more connected to the Colonial sphere than other Historic period sites in Belize (i.e., Tipu), Spanish artifacts form only a small percentage of what has been recovered from the site (Graham 2011; Pendergast 1991). This lack of Spanish artifacts contributes to the difficulty in identifying Historic period material culture (Graham 2011; Wiewall 2009). This is because, despite a variety of changes, there is still considerable continuity at Lamanai between the Terminal Postclassic and the Historic

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[22] YDL stands for *Yglesia de Lamanai* which means "Church of Lamanai" (Graham 2011:192).

period (Coyston et al. 1999; Emery 1999; Graham 2004, 2011; Pendergast 1981, 1991; White and Schwarcz 1989; White et al. 1994; Wiewall 2009; Wiewall and Howie 2010).

The arrival of the Spanish precipitated much movement about the landscape. There were many reports of people fleeing Spanish rule, at first from northern Yucatan into the relative safety of Belize, and then, as the Spanish tightened their grip, further south towards the Petén lakes (Graham 2011; Jones 1981, 1989). It has also been suggested that, during Historic times, Maya were resettled at sites like Lamanai in an attempt to more easily control and convert them (Graham 2011; Jones 1989:119-120; McKillop 2004:107).

In AD 1641, visiting friars[23] found Lamanai's second church razed and the site of Lamanai abandoned in the aftermath of the Maya rebellion. There is, however, archaeological evidence that the church was occupied following its desecration, but how soon after and for how long is not entirely clear (Pendergast 1975b, 1981:52). What is clear, however, is that Lamanai has had a long, rich history and was a major centre in the northern Maya lowlands for over a millennium.

3.3   Excavation History

Excavations at the site began in 1974 under the supervision of David Pendergast from the Royal Ontario Museum.[24] The first two field seasons were focused on the church and the southern portion of the site, revealing significant evidence of the site's Postclassic occupation (see Figure 3.1-3 for site map and Table 3.2-1 for time period dates) (Pendergast 1975a, 1975b, 1981). From there, the focus shifted to the southernmost major ceremonial structure (N10-9), as well as a number of other buildings in the ceremonial precinct and a few structures in the site's north end (Pendergast 1976, 1977a, 1977b, 1978, 1979, 1980a-d, 1981, 1982b). At the time of the first major published report, ~ 5% of the site's over 718 structures had been investigated; however, due to a

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[23] From the records of Fathers Fuensalida and Orbita (Pendergast 1981:52)

[24] Prior to this there was only minor work done by Thomas Gann in 1917 and surface collections done by other archaeologists (Pendergast 1981).

number of factors including logistics and weather, research up to that point was biased towards ceremonial constructions (Pendergast 1981:32). As Pendergast (1981:34) noted in his report, the picture of Lamanai that emerged is "an oddly skewed one" with more to be said about both ends of the time scale than about the Classic period, "the supposed zenith of Maya achievement". He suggests that this may be partially due to the site's unusual site plan (see section 3.1), which has impacted the sample (Pendergast 1981). The ROM's investigations of Lamanai continued until 1986.

From 1995 to 1997, minor excavations were conducted at 'Lamanai South', five mound groups approximately two miles south of the site's urban core (Howard and Graham 1998). At the main site, the second phase of excavations was begun in 1998 under the direction of Elizabeth Graham. This research was and "is aimed at clarifying periods of transition that are little known at other sites, but are well represented at Lamanai", including the Preclassic to Classic transition, the Maya "collapse", and the transition from the pre-Hispanic occupation to the Historic period (Graham 2004:223). Research was also integrated with plans to consolidate structures for tourism purposes. In addition, 1998 saw the introduction of a field school to the site by Elizabeth Graham and Laura Howard, with Scott Simmons co-directing with Laura Howard from 2001-2004. These excavations have focused on the Spanish Colonial Period residential zone. More recently, focus has turned to "off-platform" areas, in order to explore whether some conclusions have been affected by the representativeness of what has already been excavated (Simmons 2006; Wiewall 2006).

3.4 Burial Patterns

When discussing *burials*, following the lead of Coe (1959), the term will be used to refer to everything connected with the interment, including not only the individual but also the grave and the associated artifacts. Although mortuary treatments are often used to infer information about social status and identity of the deceased, philosophical-religious beliefs are also quite significant to burial practices (Carr 1995). Ideology is particularly important for mortuary ritual in Mesoamerica, where cosmological ideas often blur the boundaries between life and death (Becker 1992:193; McAnany et al. 1999:129).

Thus far, there has been no comprehensive synthesis of ancient Maya burial practices, although some early attempts were made (e.g., Ruz 1965; Welsh 1988). Part of the difficulty in creating a synthesis is the inter- and intra-site variability of Maya mortuary treatment. Primary, single interments were common and are often considered the norm (e.g., Welsh 1988); however, there are several well-documented examples of sites where this was not case (Chase and Chase 1996; Healy et al. 1998). Before the Historic period, cemeteries were not a common feature, which also contributes to the difficulty in creating generalizations and burial typologies, as burials are generally recovered in a random manner (Becker 1992). Interments were often made under or within all types of structures and dwellings. This choice of burial location has been seen by some as a way of keeping connections to ancestors (Gillespie 2002; McAnany et al. 1999), while others have suggested that in some cases these burials may be seen as dedicatory to the structure (Becker 1992). Interments of those assumed to be elites or important persons are often found in temples, ceremonial platforms, or household shrines, and these burials are often accompanied with numerous and luxurious grave goods. Grave goods are not limited to either sex, nor are they reserved solely for adults (Ruz 1965; Welsh 1988). They run the gamut from utilitarian ceramics to ritual items, with some items thought to characterize the deceased's identity or role in society (Ruz 1965), while others are thought to have a more ideological significance (e.g., shells are linked to life, water, and fertility – McAnany et al. 1999).

Welsh (1988), in his review of lowland Maya burial practices, acknowledged the aforementioned variability and identified the above patterns, as well as making note of a number of other practices that he referred to as "Pan Lowland Maya Burial Practices". These include the interment of a dish or a bowl under or above the skull (primarily in residential structures and/or simple graves), jade beads often found in the mouths of individuals[25], very few examples of cremation, and different types of sacrificial burial arrangements[26] (Welsh 1988). Welsh (1988) noted that, at all of the sites examined in his study (except Altun Ha), the majority of skeletons had their heads oriented in one

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[25] The previous two patterns were also noted by Ruz 1965.

[26] For more information on Maya sacrifice see Tiesler and Cucina 2007.

direction. He also linked burial position with the practicalities of grave type (i.e., extended in tombs, flexed in smaller graves) (Welsh 1988); McAnany et al. (1999), however, suggested that the appearance of tightly-wrapped, seated and flexed burials may represent long, drawn-out rituals involving prolonged displays of ancestors.

3.4.1   Patterns at Lamanai

Lamanai is no different than the rest of the Maya world in the variability observable among burials. There are a range of types and quantities of grave goods, burial positions, and grave types (from unlined pits to elaborate tombs). Primary interments were the norm, with only a few examples of secondary burials found at the site. Adults of both sexes, as well as juveniles, are represented at the site with no obvious differences in mortuary treatment. Although early in Lamanai's history there are a few interesting patterns worth noting (such as the "Lamanai tomb form"; Pendergast 1980c, 1981), they will not be discussed here as this thesis focuses on Lamanai's later time periods.

It appears that interment of individuals within building cores and foundations became more common in later times (Howie 2006a, 2012). This trend is not just an artifact of the excavation program, as Classic construction phases of the site's structures have been as intensively investigated as those dating to later periods (Howie 2006a, 2012). This practice also suggests an expansion of the function of some ceremonial buildings as they started to also act as "burial repositories" (Howie 2006a, 2012; Howie et al. 2010).

Beginning in the Terminal Classic, and becoming standard by the Postclassic period, was the pattern of pre-interment breakage of ceramics. These vessels appear to have been intentionally smashed and then placed alongside or scattered atop the interred individual. As the vessels are largely restorable, it is clear that in every instance pieces of each vessel are missing, which suggests that these missing fragments were retained, whether as a memento or for another reason (Howie 2006a, 2012; Howie et al. 2010). The introduction of this practice suggests not only a shift in funerary ritual, but also a shift in the beliefs surrounding the appropriate treatment and function of ceramics in this context (Howie 2006a, 2012). This pattern of intentionally smashed pottery appears at other sites, such as Santa Rita Corozal, Belize (Chase 1985), during the Postclassic period as

well. We also see the appearance of a significant amount of metal goods, particularly copper, in burials during this time, and a reduction in the amount of obsidian (Pendergast 1986b:241).

During the Postclassic period at Lamanai, many burials have been found with the body lain facing downwards with the legs bent back, feet touching pelvis. This position will be referred to as Ventrally Placed, Legs Flexed (VPLF) (Donis et al. 2011; Wrobel and Graham *in press*). These burials appear in a number of structures at Lamanai, and have also been documented elsewhere, including at the nearby site of Chau Hiix (Wrobel 2007) and in the coastal region of Belize at sites like Marco Gonzalez and San Pedro (Graham 2004:235; Graham et al. 2013).

During the Historic period, with the coming of the Spanish and Christianity, there was a change in burial practices, which included the creation and use of cemeteries. These burials are thought to represent those individuals who were adherents to the Christian faith (or whose families wished them to be buried as such). Although originally believed to be the cemetery for the large stone church (YDL II) (Pendergast 1981:52), the "burial mound" containing approximately 230 interments was revealed to be the location of the first, simpler church (YDL I) (Graham 2011). The individuals in this cemetery were interred "in a jumble that defies description" (Pendergast 1981:52), and while few associated artifacts were found, they were encountered in approximately 15% of burials (Pendergast 1986a). There was also a second cemetery identified, and although only a small portion has been excavated, it has been estimated to contain more than 400 individuals (Graham 2011). In the second cemetery, the burials are spaced at regular intervals and, as few were disturbed by later burials, it is thought they were marked in some way (e.g., wooden crosses) (Pendergast 1986a).

3.5 Individuals Available for Study

Although only a small percentage of Lamanai's overall area has been excavated, there are a large number of individuals available for study. The human remains excavated at Lamanai between 1974 and 1985 were analyzed by Dr. Hermann Helmuth of Trent University. These remains were housed at Trent University until 1998, when Helmuth

retired and their curation was transferred to Dr. Christine White of The University of Western Ontario and the second phase of excavations began. During the 2003 field season, she performed preliminary analysis of the previously unstudied human remains in the field and sampled the individuals for further analysis back in Canada. The University of Western Ontario now houses the majority of the remains from the original excavation, as well as the samples collected during the 2003 field season, which represents approximately 413 individuals.

The majority of excavated burials (~ 80%) from Lamanai proper date to the Postclassic period or later. The concentration of burials from the Postclassic period is a consequence of both research design (Graham 2004) and a change in burial practices (as discussed in section 3.4). The focus of excavation efforts (particularly the early efforts, which yielded the majority of the burials available for study) was on ceremonial structures and administrative-residential structures within the central precinct (Pendergast 1981). As a result of this approach, and the richness of the associated burial goods, the majority of the pre-Historic burials have been assumed to represent individuals of relatively high socioeconomic status or "elites" (Coyston et al. 1999; Howie 2012; Pendergast 1981; White 1997; White and Schwarcz 1989).

Complete burial information (such as body position, orientation, associated goods, etc.) is only available for approximately a third of the individuals. The age estimation and sex determination of the remains were performed previously by Dr. Hermann Helmuth and Dr. Christine White. The recovered individuals represent all of Lamanai's occupation periods and come from a number of structures and site areas (see Table 3.5-1 for Structure/Area List).

3.5.1   Previous Work on Lamanai's Skeletal Sample

With such a large, excavated skeletal population it is not surprising that many previous studies have been done on the remains, providing valuable insight into the life of the Lamaneros. Investigations into gendered food behavior (White 2005), biological stress (White 1997; White et al. 1994; Wright 1990), degenerative joint disease (Dormon 2007; McDonald 2001), genetic relationships with other Belizean sites based on dental

morphology (Lang 1990; Walper 1999; Wrobel 2004), and cranial and dental
modification (White 1996; Williams and White 2006) have all been undertaken using
Lamanai's human remains. With the exception of degenerative joint disease (Dormon
2007; McDonald 2001), it appears that Lamanai's population was in relatively good
physical health during the transition from the Classic to Postclassic period (White 1997),

Table 3.5-1 Lamanai's Relevant Structures and Areas with Brief Descriptions

Area/Structure(s)	Brief Description
Lamanai South (LA S) -2 miles south of Lamanai's urban core*	-made up of four mounds (each likely representing a plazuela group) -evidence of occupation span similar to the main site (Preclassic to Historic)

Ottawa Group
  N10-3; N10-12; N10-14
  N10-15; N10-17; N10-18;
  N10-25; N10-28
	Residential /Administrative complex
	  -originally constructed during the Classic and underwent several modifications through time
	  -thought to be the main elite complex

N9-33	Residential Structure
N9-56	Ceremonial Structure -also known as the "Mask Temple"
N10-1	Ceremonial Structure -in centre of N10-2's plaza
N10-2	Ceremonial Structure -large number of burials
N10-4	Residential/Administrative Structure -elite; large number of burials
N10-7	Ceremonial Structure -burial repository of high status individuals into Early Postclassic

N10-9	Ceremonial Structure
	  -also known as the "Jaguar Temple"
	  -originally built in the Early Classic; continued use into Postclassic

N10-43	Ceremonial Structure
	  -known as the "High Temple"
	  -originally constructed in the Preclassic

N10-66	Residential Group -borders central precinct to the west along with N10-67 and N10-68
N11-5	Residential Structure -south of central precinct in a residential zone along with Structures N11-4 and N11-9
P8-9	Ceremonial Structure -Preclassic

P8-11	Residential Structure
	  -north of central precinct
	  -dates to the Preclassic period like many of the structures in this area

P8-102	Residential Group
	  -borders the central precinct to the north with P8-103 and P8-104
	  -abandoned in Preclassic; new construction occurred during the Terminal Classic

YDL; N12-11	-Historic Period Cemetery

*Not pictured in Figure 3.1-3.

but the transition to the Spanish Colonial period is associated with increased biological stress (White 1986; White et al. 1994; Wright 1990).

Isotopic work has also been done on a number of individuals that are currently in Western's inventory. Diet has been reconstructed through time using carbon- (from both collagen and carbonate) and nitrogen-isotope data (Coyston 1994; Coyston et al. 1999; White 1986; White and Schwarcz 1989). Maize was a dietary staple, although the Lamaneros enjoyed a mixed diet that changed through time (Coyston 1994; Coyston et al. 1999; White 1986; White and Schwarcz 1989). After a reduction in the consumption of maize in the Terminal Classic, isotopic analyses indicate a significant increase in the consumption of both maize and marine resources during the Postclassic period continuing into Historic times (Coyston 1994; Coyston et al. 1999; White 1986, 1997; White and Schwarcz 1989). Phosphate-oxygen isotope analysis, along with the previously produced diet data, was used by White et al. (2009) to explore the possibility of a West Mexican origin of a joint burial referred to as "The Loving Couple". More recently, Howie et al. (2010) performed a variety of isotopic analyses (oxygen and carbon from carbonate, and carbon and nitrogen from collagen) in order to explore the life histories of individuals from a number of residential groups dating to the Terminal Classic and Early Postclassic periods. These data were combined with stylistic and petrographic analyses of accompanying burial vessels, and, among the many insights into economic relationships (e.g., connections to both local and non-local pottery producers) and food consumption patterns (e.g., elite consumption of maize-fed terrestrial animals), they provide possible evidence for maintenance of foreign traditions (Howie et al. 2010). The insights gained from these studies along with their data are incorporated into this project, and the previous isotopic work helped to inform this study's sample selection process.

3.6 Sample Selection

3.6.1 Skeletal Sample

Because of the large number of individuals available for study from Lamanai it was not possible (due to budgetary and time constraints) to include them all. Therefore, a feasibly sized sample suitable to address the questions of interest was selected.

Lamanai was occupied from the Preclassic to Historic period with human remains recovered from each time period[27]. This study, however, focuses only on the Postclassic and Historic periods. A similar number of individuals was selected from each time period in order to facilitate comparisons. In order to explore possible mobility differences by sex and age, an attempt was made to include both males and females, as well as individuals of a variety of ages from each time period. Individuals with the most detailed and complete records (e.g., burial information, cranial and/or dental modifications, etc.) were given priority. Individuals interred in the VPLF burial position (see section 3.4) are specifically under investigation, and therefore all available identified VPLF Postclassic individuals were selected.

For isotopic analysis, the availability of desired tissues (i.e., a tooth and a bone) and good preservation were determining factors for sample selection. The Lowland Maya region is particularly inhospitable for good skeletal preservation due to its tropical climate and alkaline soil chemistry, but additional preservation problems can also be created by extensive root growth, insect action, displacement by burrowing animals, mortuary treatment, excavation, and storage methods.

As discussed in section 2.2, different tissues provide information on different times in an individual's life. To get the most complete picture of each individual's mobility through his or her lifetime, it is optimal to select a tooth (to represent childhood) and a bone (to represent the later years of life). Ideally, the same type of tooth should be selected from each individual. Permanent first molars were given preference due to their early formation[28], but were not always available.

The likelihood that a sample retains its original isotopic composition also needs to be assessed (see section 2.7). Sample preservation was initially informally assessed

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[27] Data recording sheets and previous studies dealing with the human remains (e.g., White 1986) have grouped the burials into six time periods (Preclassic, Early Classic, Late Classic, Terminal Classic, Postclassic, and Historic), and for continuity the information discussed here is categorized in the same fashion.

[28] As first molars are one of the first "adult" teeth that form, they are present in a wide age range of individuals.

visually, based on apparent condition (e.g., overall appearance, friability, etc.) and priority was given to the least friable samples[29]. Individuals whose bone provided usable isotopic results in previous diet studies (Coyston et al. 1999; White 1986) were also given priority. All Postclassic and Historic period individuals from these earlier studies whose remains are clearly marked and stored at Western were included in the present study (n = 22), including some of those individuals for whom preliminary phosphate-oxygen isotope values were reported in White et al. (2009). Howie et al. (2010) did not use any individuals from previous isotopic studies, but did obtain $\delta^{18}O$ values for structural carbonate (along with diet data) from 24 other individuals. These $\delta^{18}O_{sc}$ values can be converted to phosphate-oxygen isotope values using an equation (section 5.3.5.2), and will be used during discussion of the more complete Lamanai data set.

Ultimately, a total of 116 unique bone and tooth samples were selected for this study, representing 63 individuals – 36 from the Postclassic (including 21 in the VPLF position) and 27 from the Historic period. Appendix A provides detailed information about each individual.

3.6.2   Water Sample

Although it is not within the scope of this thesis to do an extensive investigation of drinking water sources at Lamanai, an effort was made to collect and analyze water from various sources to help inform the baseline and variability for the locality. Two major sources of drinking water available to the Lamaneros were the lagoon and shallow groundwater (e.g., natural freshwater springs). Samples of both lagoon water (taken from the North Dock) and groundwater (from a well in the town of Indian Church) were collected once a month from May 2008 to April 2009. In addition, spot samples were collected from various locations around the lagoon during June 2008, including the point where the New River meets the lagoon and points along two small creeks that lead out of the lagoon. Single samples of groundwater were also collected from other town wells and local freshwater springs. In addition, since other local sources of water may have

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[29] After the sample selection process, more quantitative methods are used to determine whether isotopic analysis can proceed and whether the isotopic results obtained represent unaltered material (section 5.1).

also been available to people living in and around Lamanai, single samples from various smaller water sources (i.e., ponds) were collected opportunistically to get some idea of local variability in water isotopic composition. Samples of precipitation events were also collected during the May/June 2008 field season. More details concerning the water samples are provided in Appendix B.

Chapter 4

4 Methods

4.1 Preparation of Silver Phosphate (Ag_3PO_4)

The preparation of silver phosphate (Ag_3PO_4) from bone and enamel for oxygen-isotope analysis of phosphate-oxygen follows the standard protocol of the Laboratory for Stable Isotope Science (LSIS) at the University of Western Ontario. This method is based on the work of Stuart-Williams (1996), Firsching (1961), and Crowson (1991). The process for obtaining Ag_3PO_4 from bone and enamel for isotopic analysis requires essentially three steps: cleaning and dissolving the sample, removing the calcium and organics, and precipitating and isolating the Ag_3PO_4.

Both bones and teeth were gently cleaned under distilled water using a toothbrush to remove excess dirt and then allowed to air dry. A wire brush was used to remove any remaining visible dirt, as well as the friable trabecular bone. Dental picks and tweezers were used to remove stubborn trabecular bone and to separate dentine from enamel. Using a mortar and pestle, the cortical bone and enamel samples were ground to a fine powder. Between 30 and 35 mg of each sample were then weighed into 15 mL vials. The vials were filled with 3 M acetic acid and left at room temperature until bone or enamel powder was dissolved (at least overnight for bone and 48 hours for enamel). Samples were usually prepared in groups of six.

Once the samples dissolved, they were transferred to centrifuge tubes. Two millilitres of 0.55 M potassium oxalate was added to each tube and the pH was adjusted to 3.5–4.0 with drops of 8 M potassium hydroxide (KOH). After the samples were allowed to react for five minutes, they were centrifuged. As this step's purpose was to remove the calcium, the calcium oxalate precipitate was discarded. Lead acetate (5 mL of 0.5 M) was then added to the supernatants. The pH was adjusted with 8 M KOH to between 5.3 and 5.5, and the solution was again allowed to react for 5 minutes. The samples were centrifuged and the supernatants discarded.

The lead phosphate precipitate then underwent a treatment to remove traces of the potassium oxalate and any organics. One millilitre of 6 M nitric acid (HNO_3) and 1.5 mL of 30% hydrogen peroxide (H_2O_2) were added to each sample and they were placed in a 95 ˚C water bath for 20–30 minutes. The samples were then transferred into glass tubes and again treated with 1 mL of HNO_3 and 1.5 mL of H_2O_2. Additional H_2O_2 was added dropwise to rinse down material sticking to the sides of the tubes. The liquid in the tubes was allowed to evaporate to just above the white crystals at the bottom, at which point a small amount of Millipore water was used to rinse down the sides of the tubes. This wash and evaporate cycle was repeated three times to ensure that all H_2O_2 had reacted completely.

The samples were then allowed to cool outside of the water bath. Once the samples had cooled, 8 M KOH was added dropwise to each sample, raising the pH until the crystals dissolved. The samples were then transferred to clean centrifuge tubes, and 3 mL of 0.5 M lead acetate was added to each. To produce lead phosphate precipitates, the sample pH was carefully adjusted to between 5.5 and 5.7 using a combination of 8 M and 4 M KOH. After allowing five minutes for the reaction, the samples were centrifuged and the supernatants (containing excess lead acetate) were discarded. Next, 2 mL of 0.25 M HNO_3 was added to the lead phosphate precipitates, and each sample was dissolved using a stirring rod and a few additional drops of HNO_3. To each dissolved sample, 2 mL of 0.25 M ammonium sulphate was added in order to remove the lead in the form of a lead sulphate precipitate. The samples were allowed to react for five minutes before they were centrifuged. The supernatants were retained and transferred to 80 mL beakers.

To each beaker, one to two drops of pH indicator, bromothymol blue, was added, as well as enough Millipore water to ensure that a reading could be obtained using the pH meter. Using drops of 4 M KOH the pH was adjusted to between 5.5 and 6.5, turning the solution a yellow-green. If necessary, 1 M acetic acid was added if the pH became too basic and the solution turned blue. After this, the solutions were poured into centrifuge tubes for one last centrifugation to ensure that all of the sulphate was removed. The supernatants were returned to their rinsed beakers.

The next step was the isolation and precipitation of Ag_3PO_4 through ammonia volatilization. To do this, it was first necessary to create an ammoniacal silver solution, by dissolving 3.6 g of silver nitrate in 60 mL of Millipore water and then adding ammonium hydroxide (NH_4OH) dropwise until the solution became clear. Then, approximately 10 mL of the ammoniacal silver solution, 1 mL of NH_4OH, and 1.5 mL of ammonium nitrate were added to each beaker, along with enough Millipore water to fill the beakers to the 70 mL level. The beakers were placed on a 55 ˚C hotplate for 6–7 hours. Millipore water was added periodically to maintain the liquid level.

After 6–7 hours, precipitation of Ag_3PO_4 crystals was complete and, once cooled, no ammonia smell remained. The beakers were then scraped with a Teflon spatula to loosen the precipitate, and the solution was poured through a fritted glass filter over a vacuum flask. The beaker was then rinsed three times with a small amount of Millipore water, filtering each time. Care was taken to retain most of the precipitate in the beaker throughout the filtering process to minimize sample loss. The Ag_3PO_4 crystals on the filter were then returned to their original beaker and the samples were placed in a 60 ˚C oven to dry. Once dry, the samples were scraped out of the beakers into small, stoppered 1 dram vials. After the weights were recorded and yields calculated, they were stored in sample boxes.

4.2   Oxygen Extraction from Silver Phosphate

To extract oxygen from the Ag_3PO_4 that was precipitated from the samples, the LSIS standard protocol was used. The protocol follows procedures that have been adapted from Clayton and Mayeda (1963), Crowson et al. (1991), Taylor and Epstein (1962), and Stuart-Williams and Schwarcz (1995). A maximum of six samples were extracted in each run and, among these six, at least one Ag_3PO_4 standard (337382 Aldrich, Lot 03610EH) was always included. Approximately 25–30 mg of Ag_3PO_4 was loaded into nickel reaction vessels inside a dry glove box (relative humidity <13%). The samples were heated overnight (~ 15–18 hours) at 100 ˚C under vacuum, and then at 300 ˚C for 2 hours. The reaction vessels were then cooled, frozen with liquid nitrogen, and 80 mmHg of bromine pentafluoride (BrF_5) was transferred into each. Once the transfers were complete, the vessels were heated to 600 ˚C for approximately 18 hours; at this

temperature, BrF_5 reacts with Ag_3PO_4 to liberate the oxygen. This oxygen is then converted to carbon dioxide (CO_2) by reacting it with graphite and heat. A manometer was used to measure the yield of CO_2. Each gas sample was then analyzed for its oxygen-isotope composition using one of the LSIS VG Optima, Prism II, Thermo Finnigan Delta^{plus} XL, or Thermo Finnigan Delta V Plus mass spectrometers in their dual-inlet mode, depending on instrument availability.

The yields of sample CO_2 averaged 4.95 ± 0.16[30] µmol/mg (n = 234) and the Aldrich standard averaged 4.81 ± 0.20 µmol/mg (n = 84), as compared to the theoretical value of 4.76 µmol/mg. The oxygen isotopic results obtained were expressed relative to Vienna Standard Mean Ocean Water (VSMOW) in standard δ notation (see section 2.1). A small correction calibrated using internal standard results was applied to samples analyzed from June to August 2011, due to unusually high humidity in the laboratory. The $\delta^{18}O$ value of the Aldrich standard averaged $+11.48 \pm 0.59$ ‰ (n = 84), as compared to its accepted value of $+11.3$ ‰. The average reproducibility of the oxygen isotopic measurements of sample method duplicates (different precipitation and extraction of Ag_3PO_4) was ± 0.24 ‰ (n = 36; 73 analyses).

 Not all samples analyzed during the course of these experiments pertain to the time periods or populations ultimately selected for discussion in this thesis. These additional data are therefore not discussed further here.

4.3   Collagen Extraction and Analysis

Collagen was extracted from bone samples using the LSIS standard protocol, which is modified from the Longin (1971) method. In short, the mineral portion of the bone is dissolved in weak hydrochloric acid (HCl) leaving an insoluble collagen residue. This residue is treated with sodium hydroxide (NaOH) to remove fulvic and humic acids from the sample. After the NaOH treatment, the residue is heated, gelatinizing the collagen. The collagen is then dried.

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[30] Reproducibility and precision measures are reported throughout this thesis as ± one standard deviation.

The details of the procedure are as follows. Bone samples, which were cleaned and ground as described in section 4.1, were sieved. The sieved portion between 0.85 and 0.18 mm in size was used, as the speed of demineralization depends on the size of the bone fragments. A consistent size encourages more consistent demineralization speeds (and prevents unnecessary yield decreases). Approximately 0.4 ± 0.1 g of sample was weighed out and placed into 11 mL 16 x 100 mm glass culture tubes.

Lipids were extracted by rinsing the samples three times with a 2:1 chloroform : methanol solution. This rinse was done by adding ~ 8 mL of solution to each sample, allowing it to sit for 15 minutes, and then using a Pasteur pipette vacuum to remove the liquid. The samples were allowed to dry overnight uncapped in a fume hood.

The next step was the slow dissolution of the bone's inorganic portion in weak HCl. Approximately 8 mL of 0.25 M HCl was added to the culture tubes, which were agitated and then allowed to sit for two hours. After the two hours, the samples were centrifuged, the liquid pipetted off, and ~ 8 mL of 0.5 M HCl was added to each tube. After agitation, the sample tubes were placed in an angled rack[31] for one to two days. At least every 48 hours, the samples were centrifuged, the liquid pipetted off, and the samples' level of demineralization tested by pressing the bone fragments against the side of the tube. If the bone fragments were not fully demineralized, ~ 8 mL of 0.5 M HCl was added and the cycle continued until the samples were demineralized. A sample was considered fully demineralized when all of the bone fragments were "ghosted" (translucent and soft).

Once the sample was fully demineralized and as much HCl as possible was removed by pipetting, the sample was rinsed by adding ~ 8 mL of distilled water, centrifuging the sample, and again removing the liquid by pipetting. This was done three times, then the liquid of about a quarter of the samples, randomly selected, were tested to ensure the pH was higher than 2.5 (if not, additional water rinses were performed).

After removing the final rinse of distilled water, the humic and fulvic acids were removed by adding ~ 8 mL of 0.1 M NaOH to the culture tubes. The samples sat for 20 minutes,

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[31] The test tube rack was angled in order to maximize surface exposure of the sample within the tube.

being periodically agitated. The samples were then centrifuged and colour changes observed. If the solution changed colour, then humic and fulvic acids were assumed to be present, and this step was repeated. Once no colour change was observed, the NaOH was removed and the samples were rinsed at least six times with distilled water until the liquid attained a pH of between 6 and 8.

The next step made the extracted collagen water-soluble by heating it in a weak acid. After the removal of the distilled water from the last rinse, ~ 8 mL of 0.25 M HCl was added to the samples. The samples were agitated and centrifuged immediately, and as much HCl as possible was removed by pipetting. Approximately 3 mL of distilled water was added to each of the samples, and the pH of each tested. The target pH was ~ 2.5; if it was higher than 3.5, a drop or two of weak acid (0.25 or 0.001 M HCl) was added. The samples were then capped and placed in a 90°C oven for at least 16 hours.

 After the collagen had solubilized and dissolved, the samples were centrifuged and the liquid pipetted into 4 mL glass vials. These uncapped vials were then placed in the 90 °C oven in beakers for drying. The dried samples were weighed and then ground to homogenize them. Collagen yields were calculated by dividing the weight of the extracted collagen by the initial sample weight. Duplicate extractions were performed on ~ 19% of the sample, with the average reproducibility of the yields being ± 0.2% (n = 7).

Each sample with a collagen yield ≥ 1% (see section 5.1.5) was weighed into tin cups (goal weight: Batch 1 = 0.505 ± 0.015 mg; Batch 2 = 0.395 ± 0.010 mg), rolled into tight balls and stored in a desiccator until analysis. Nitrogen- and carbon-isotope ratios were obtained using a Costech elemental combustion system (ECS 4010) coupled with a Thermo Finnigan Delta V Plus isotope-ratio mass-spectrometer in continuous flow mode. The carbon isotopic results obtained are expressed relative to Vienna Pee Dee Belemnite (VPDB) and the nitrogen isotopic results relative to atmospheric nitrogen (AIR), both in standard δ notation (see section 2.1).   The δ^{13}C values were calibrated to VPDB using either the combination of NBS-22 (accepted value = –10.45 ‰) and IEAE-CH-6 (accepted value = –30.03 ‰) or USGS-40 (accepted value = –26.39 ‰) and USGS-41 (accepted value = 37.63 ‰). The δ^{13}C value of IAEA-CH-6 standard when analyzed as

an unknown averaged -10.55 ± 0.06 ‰ (n = 3), as compared to its accepted value of -10.45 ‰. The $\delta^{15}N$ values were calibrated to AIR using USGS-40 (accepted value = -4.52 ‰) and USGS-41 (accepted value = $+47.63$ ‰). The $\delta^{15}N$ value of the IAEA-N2 standard was $+20.54 \pm 0.05$ ‰ (n = 4), as compared to its accepted value of $+20.30$ ‰. The $\delta^{13}C$ value of the keratin standard averaged -24.06 ± 0.05 ‰ (n = 15) over all analyses, as compared to its accepted value of -24.04 ‰, and the $\delta^{15}N$ value averaged $+6.39 \pm 0.12$ ‰ (n = 14), as compared to its accepted value of $+6.36$ ‰. Sample duplicates from the same collagen extraction had an average reproducibility of ± 0.01 ‰ (n = 6) for $\delta^{13}C$ and ± 0.02 ‰ (n = 6) for $\delta^{15}N$, which indicates not only good precision, but also homogeneity in the ground samples. Average reproducibility of method duplicates (sample replicates prepared from a fresh aliquot of the unprocessed sample) was ± 0.02 ‰ (n = 6) for $\delta^{13}C$ and ± 0.05 ‰ (n = 6) for $\delta^{15}N$, confirming the consistency of the collagen extraction method.

The atomic carbon to nitrogen ratio (C:N) for each collagen sample was also determined during the analysis. It was calculated using the known proportions of C and N in the standards, the weights of the samples and standards, and the area of the mass 44 ($^{12}C^{16}O^{16}O$) and mass 28 ($^{14}N^{14}N$) peaks detected by the mass spectrometer for the CO_2 and N_2 gas. The percent weights for each sample were then normalized using the atomic weights of carbon and nitrogen. The keratin standard C:N ratio was reproducible to $\pm$ 0.09 (n = 15). The C:N ratio of the sample duplicates from the same collagen extraction had an average reproducibility of ± 0.00 (n = 6); method duplicates had an average reproducibility of ± 0.02 (n = 6).

4.4 Assessing Diagenesis

As discussed in section 2.7.2, Fourier Transform Infrared (FTIR) spectroscopy is an analytical method used in archaeology to assess post-mortem alteration of bioapatite by allowing investigation of crystallinity, carbonate content, and the presence of minerals indicative of diagenetic change. In this method infrared radiation is passed through a sample. Some of this radiation is absorbed, while the rest is transmitted through the sample, resulting in a spectrum representing its "fingerprint" as it is the structure of the phases present in a sample that determines which wavelengths are transmitted or

absorbed. Each absorbance peak on the produced spectrum represents a specific configuration of atoms that react in a certain way when they are excited by the IR radiation. The height of the peak represents the intensity of absorbance, which is proportional to the concentration of the absorbing molecule or ionic substance (Smith 2011). Using these peaks, the crystallinity index (CI) and carbonate content (C/P) can be calculated, and diagenetic indicator minerals can also be observed. Through these observations and calculations, changes to the bioapatite and the introduction of secondary phases that occurred during diagenesis can be inferred. FTIR analysis was conducted for all samples in this thesis (bone and enamel) and both calculations, as well as observations of diagenetic indicator minerals, were considered for all samples.

For the production of the spectra and the calculation of the CI, the LSIS standard protocol was followed, which is based on the methods developed by Shemesh (1990), Weiner and Bar-Yosef (1990), Wright and Schwarcz (1996), and Surovell and Stiner (2001). Bone and enamel samples were first cleaned and ground as described in section 4.1, and then sifted through nested 63 μm and 45 μm sieves. This is done to regulate grain-size, as grain-size can affect CI results (Surovell and Stiner 2001). A 12 mm diameter pellet was formed by compressing a mixture of 2.0 ± 0.1 mg of the powdered sample with 200 ± 2.0 mg of potassium bromide (KBr) in a hydraulic press set at 10 tons for 10 minutes. The pellet was then placed inside a Bruker Vector 22 FTIR Spectrometer. Using the OPUS NT program[32], the transmission spectrum was recorded between 400 and 4000 cm^{-1} using 16 scans and a resolution of 4 cm^{-1}.

The calculation of CI uses the double absorbance peaks created by orthophosphate between 550 and 650 cm^{-1} (Surovell and Stiner 2001). The CI is actually a measure of the splitting between these two peaks (Shemesh 1990). High CI values are generally the result of tall, well-separated peaks and indicate large, well-ordered crystalline structures, whereas a greater overlap, small peaks, and a shallow valley result in low CI values and usually indicate less ordered crystalline structures (Shemesh 1990; Weiner and Bar-Yosef

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[32] The OPUS NT program is software used with the FTIR spectrometer to measure, process, and evaluate IR spectra.

1990; Wright and Schwarcz 1996). To calculate the CI, the baseline was first corrected by drawing a straight line between 495 and 750 cm^{-1} (Weiner and Bar-Yosef 1990). The heights at the absorbance peaks nearest 565 and 604 cm^{-1} were recorded and combined, and then divided by the height of the valley between them. The crystallinity index formula is:

$$CI = (A + B) / C,$$

where A is the height from the baseline to the peak closest to 604 cm^{-1}, B is the height from baseline to the peak closest to 565 cm^{-1}, and C is height from baseline to the valley between the two peaks.

A different area of the spectrum is used to calculate C/P. The ratio between the absorbances of carbonate (CO_3) and phosphate (PO_4) can be used to estimate the structural carbonate content of a sample (Wright and Schwarcz 1996). This study, following Wright and Schwarcz (1996), uses C/P, the ratio of the CO_3 peak at 1415 cm^{-1} and the major PO_4 peak at 1035 cm^{-1}. Values significantly different than those expected for unaltered tissue can indicate diagenetic changes. In addition, the amount of CO_3 in a sample can affect the crystallinity index, as B-type CO_3 substitutions produce smaller crystals with greater strain (Wright and Schwarcz 1996).

Duplicate analysis, which involved analysis of separately prepared discs, was conducted on approximately 16% (n = 19) of analyzed samples (11 of which appear in this thesis). The average reproducibility of the C/P ratio was ± 0.03 (n = 19), and CI values were reproducible to ± 0.04 (n = 19)[33].

For each sample the presence or absence of an absorbance peak at 710 cm^{-1} and 1096 cm^{-1}, representing calcite and francolite (fluorapatite) respectively, was also noted (Lee-Thorp and van der Merwe 1991; Shemesh 1990; Wright and Schwarcz 1996). The presence of these phases is a strong indicator of post-mortem sample alteration.

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[33] Sample N10-2/21 M2's data was excluded from the reproducibility calculations; the CI value obtained during its duplicate analysis was a very large outlier from the rest of the data set.

4.5 Oxygen-Isotope Composition of Water

Water samples for this study were collected following the same protocol by multiple individuals from May 2008 to July 2009. For each sample, the water collection bottle and lid were first rinsed three times in the water to be sampled. The container was then filled with water and capped while completely submerged to avoid allowing air into the bottle. The cap was then screwed closed, the container removed from the water, and dried off. The bottle was then further sealed with electrical tape and the sample number, date, and water source was recorded both on the bottle itself and on the electrical tape.

The water samples were analyzed by LSIS staff using various combinations of three methods to determine the $\delta^{18}O$ and δ^2H values. Of the samples used in this thesis, determination of the $\delta^{18}O$ values of some samples (n = 8) was done using a Thermo Finnigan Gas Bench II device interfaced with a Delta^{plus} XL isotope-ratio mass-spectrometer in continuous flow mode. The determination of the δ^2H values of most of these samples as well as many others (total n = 28) was done using the LSIS standard protocol for the conversion of liquid H_2O into H_2 gas in a vacuum line using zinc, drawing from the work of Coleman et al. (1982), Tanweer et al. (1988), and Vennemann and O'Neil (1993). The H_2 gas was then analyzed using the PRISM II isotope-ratio mass-spectrometer. All of the samples were also analyzed for both oxygen and hydrogen isotopic compositions using the Picarro L1102-i Isotopic Water Liquid Analyzer, which employs a different technology (cavity ring-down spectroscopy) to obtain the measurements. All of methods gave similar results as discussed below.

The oxygen and hydrogen isotopic results are expressed relative to VSMOW in standard δ notation (see section 2.1). The $\delta^{18}O$ and δ^2H values were calibrated to VSMOW using in-house laboratory standards Heaven and LSD, with accepted $\delta^{18}O$ values of –0.27 ‰ and –22.6 ‰, respectively, and δ^2H values of +88.7 ‰ and –161.8 ‰, respectively. These in-house laboratory standards, as well as the in-house standards MID and EDT, were calibrated against the international standards VSMOW and SLAP described in Coplen (1994). The $\delta^{18}O$ values of the analyzed standards were –7.23 ± 0.12 ‰ (n = 27) for EDT, as compared to its accepted value of –7.27 ‰, and –13.05 ± 0.09 ‰ (n = 10) for MID as compared to the accepted value of –13.08 ‰. The δ^2H values of the analyzed

standards were -55.5 ± 1.4 ‰ (n = 32) for EDT, as compared to the accepted value of -56.0 ‰, and -109.0 ± 2.2 ‰ (n = 14) for MID as compared to the accepted value of -108.1 ‰. The reproducibility of samples averaged ± 0.10 ‰ for $\delta^{18}O$ values, and ± 2.0 ‰ for $\delta^{2}H$ values across all of the methods used.

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Chapter 5

5   Results and Discussion

After presentation of the tests for port-mortem alteration and the water data, this chapter is broken into three main sections: examination of phosphate-oxygen isotopic data, investigation of diet using collagen carbon- and nitrogen-isotope data, and the exploration of the individuals buried in the VPLF position. All statistics were produced using IBM SPSS Statistics 21. Normality was assessed visually and through the Shapiro-Wilks test, and outliers were tested for using boxplots. In every case where the necessary statistical assumptions of a test may have been violated (e.g., normality) both the parametric and non-parametric version of the test were used. For comparison of two groups the parametric independent t-test and the corresponding non-parametric Mann-Whitney U test were used; likewise for testing association between variables Pearson's correlation and Spearman's correlation were used. If both tests produced a similar result, the result of the parametric test was reported for consistency. As with many archaeological studies using human remains, this study deals with small sample sizes which can sometimes preclude reliable assessment of statistical significance, particularly when combined with unequal sample sizes. In an attempt to avoid spurious results, the following approach was adopted: statistical analysis was not performed if a sample size was < 10 and one sample was more than twice the size of the other.

5.1   Tests for Post-Mortem Alteration

With archaeological samples there is always the concern that their isotopic compositions may have changed over time due to diagenetic processes. Several steps were taken to assess the level of diagenetic alteration. To examine the mineral phase of the bones and teeth, FTIR was used to determine crystallinity index (CI), the carbonate/phosphate ratio (C/P), and the presence of specific diagenetic indicator minerals. In addition, possible correlations between $\delta^{18}O_p$ values and a number of factors were also used to assess the reliability of the results. The preservation of the collagen component of bone was

assessed using several measures, including collagen % yield, C:N ratio, and testing for correlations between these parameters and $\delta^{13}C$ and $\delta^{15}N$ values.

5.1.1   Crystallinity Index

As samples undergo diagenetic recrystallization, bioapatite crystals are expected to become larger and more ordered, which increases crystallinity. Crystallinity index (CI) values of 2.6 to 3.1 have been reported for fresh, modern human bones (Nielsen-Marsh and Hedges 2000; Wright and Schwarcz 1996), whereas archaeological bones commonly have slightly higher values (~ 2.8 to 3.9), with a CI > 4.0 being considered as extremely degraded (e.g., Smith 2007). The average CI for all samples (bone and tooth enamel) in this thesis for which $\delta^{18}O_p$ values were also obtained is 2.8 ± 0.2 (n = 116), which falls within the expected range. However, within the overall range of values (2.4–3.3) there are some unexpectedly low values.

Comparing CI values directly with those from other studies can be misleading in some cases because the grain-size of the sample can affect CI values (Surovell and Stiner 2001), as can the timing of CI measurements (e.g., before any treatment, after treatment with acid, etc.; Wright and Schwarcz 1996). As discussed in section 4.4, there was no pre-treatment of the samples and the grain-size used in this thesis was standardized to 45–63µm. This methodology is directly comparable to Olsen's (2006) and Metcalfe's (2005) studies of neighbouring sites in Belize (see Table 5.1-1).

Table 5.1-1 Mean and Range of CI Values

	n	Mean CI Value	Range in CI Values
Total Sample	116	2.79 ± 0.18	2.38–3.26
Bone	58	2.90 ± 0.13	2.66–3.26
Enamel	58	2.68 ± 0.16	2.38–3.04
Altun Ha*	63	3.00 ± 0.25	2.63–3.56
Chau Hiix Bone†	29	3.00 ± 0.30	2.70–4.10
Chau Hiix Enamel†	30	2.60 ± 0.30	2.20–3.40

*(Olsen 2006)

†(Metcalfe 2005)

When the CI values from this study are examined by tissue type, there is a statistically significant difference between bone and enamel [t(114) = 7.676, p < 0.0005] with the average CI for bone being 2.9 ± 0.1 (n = 58) and tooth enamel being 2.7 ± 0.2 (n = 58).

All bone CI values fall within the expected range discussed. However, some of the tooth enamel values are low, especially when compared to the CI of fresh bone (enamel is generally understood to have a higher crystallinity than bone). As can be seen in Table 5.1-1, however, the enamel CI values from Chau Hiix (Metcalfe 2005; J. Metcalfe et al. 2009) are even lower than those obtained here. Metcalfe (2005) and J. Metcalfe et al. (2009) suggest that the unusually low values were likely not indicative of a problem that would affect $\delta^{18}O_p$ results as there was no correlation found between the CI values and the isotopic results (Metcalfe 2005; J. Metcalfe et al. 2009). This is also the case in this study, as is discussed in section 5.1.4.

5.1.2   C/P ratios

The ratio (C/P) between the FTIR absorbances for carbonate (CO_3) and phosphate (PO_4) can be used to estimate a sample's structural carbonate content (Wright and Schwarcz 1996). In bone, natural biogenic carbonate has a C/P ratio of ~ 0.360 (Brock et al. 2010). C/P ratios > 0.4–0.5 indicate alteration, commonly the addition of secondary carbonate (Nielsen-Marsh and Hedges 2000; Smith et al. 2007). Ratios < 0.3 may also indicate alteration (e.g., through the loss of carbonate due to post-depositional recrystallization), with ratios of 0.1 being considered heavily degraded (Nielsen-Marsh and Hedges 2000; Smith et al. 2007). The average C/P for all samples (bones and teeth) for which $\delta^{18}O_p$ values were obtained is 0.38 ± 0.06 (n = 116), ranging from 0.24 to 0.51. Accordingly, the majority of samples do not appear to be significantly altered. Overall, tooth enamel has slightly lower C/P ratios (0.36 ± 0.06, n = 58) than bone (0.40 ± 0.05, n = 58), but this is not surprising as enamel apatite usually incorporates less carbonate than bone apatite.

5.1.3   Calcite and Francolite (Fluorapatite)

Calcite, which can precipitate on and within pore space in bone and tooth during diagenesis, is detectable by a peak at 710 cm^{-1} on a FTIR spectrum. No calcite peaks were detected in any of the samples.

A peak at 1096 cm^{-1} in a FTIR spectrum is characteristic of francolite/fluorapatite, which indicates diagenetic change related to incorporation of fluoride (F$^-$) into bioapatite. Small

amounts of fluorine occur naturally in bioapatite, so a slight "shoulder" around 1096 cm^{-1} is not unexpected (Wright and Schwarcz 1996). The peak-pick function of the OPUS NT software was used to standardize the identification of a distinct (likely diagenetic) peak versus a biogenic "shoulder". When the presence of a peak near 1096 cm^{-1} was registered at 1% sensitivity using the peak-pick function, a peak was recorded as present. Only bone from individual N10-1/2 clearly contained a francolite/fluorapatite peak. Accordingly, and also because of its low collagen yield (see section 5.1.5), no isotopic analysis was performed on this sample.

5.1.4   Test Correlations for Bioapatite

Another means for assessing diagenesis (as well as identifying changes possibly caused by methodology) is to search for correlations between $\delta^{18}O_p$ values and various measures, such as CI, C/P, Ag_3PO_4 yields, and CO_2 yields. The results of these tests are given in Table 5.1-2. If the $\delta^{18}O_p$ values were changed during diagenetic recrystallization, a correlation between CI and $\delta^{18}O_p$ would be expected. If original $\delta^{18}O_p$ values were altered by diagenetic changes to the carbonate or phosphate contents of the sample, a correlation between C/P and $\delta^{18}O_p$ would be expected. As seen in Table 5.1-2, no correlations are present for either pairs of values, suggesting that original $\delta^{18}O_p$ values have not been significantly modified.

Tests for laboratory-induced effects on $\delta^{18}O_p$ values were also performed. If conversion from Ag_3PO_4 to CO_2 gas was incomplete, a correlation would be expected between CO_2 yields and $\delta^{18}O_p$ values; this is not the case (Table 5.1-2). If precipitation of Ag_3PO_4 were incomplete (resulting in either the preferential recovery of ^{16}O or ^{18}O), then a correlation between Ag_3PO_4 yields and $\delta^{18}O_p$ values would be expected. Only a "moderate" correlation was observed (Table 5.1-2). The overall range of variation in $\delta^{18}O_p$ values in this study is quite small; removal of the samples that contribute to this possible correlation does not significantly affect the overall group statistics or anthropological interpretations. Accordingly, these sample results were retained.

Table 5.1-2 Bioapatite Correlation Tests

Test Correlation	Test Group	Result
CI values and $\delta^{18}O$ values	Bone	Pearson's r = –0.014, df = 56
	Enamel	Pearson's r = –0.242, df = 56
C/P ratios and $\delta^{18}O$ values	Bone	Pearson's r = –0.212, df = 56
	Enamel	Pearson's r = 0.110, df = 56
Ag_3PO_4 yield and $\delta^{18}O$ values	Bone	Pearson's r = –0.395, df = 74
	Enamel	Pearson's r = –0.418, df = 64
CO_2 yield and $\delta^{18}O$ values	Bone	Pearson's r = –0.224, df = 75
	Enamel	Pearson's r = –0.230, df = 64

5.1.5   Collagen Diagenesis

Preservation of bone collagen for those samples analyzed for $\delta^{13}C$ and $\delta^{15}N$ values was assessed using collagen yield and C:N ratio. By weight (wt), fresh modern bone usually consists of ~ 22% collagen (van Klinken 1999); however, significantly less is expected in archaeological bone. Samples with collagen yields < 1% have been shown to have unreliable collagen δ-values (Dobberstein et al. 2009; van Klinken 1999). Of the individuals for which bone collagen was extracted for this study, 4 out of 37 had yields < 1% and therefore were not analyzed for carbon or nitrogen isotopic composition. In addition, as it has been suggested that the presence of collagen insulates the mineral portion of the bone from alteration (e.g., Hedges 2002; Nielsen-Marsh and Hedges 2000; Trueman et al. 2004), the majority of samples deemed to have unacceptably low collagen yields for collagen analysis (n = 3) were not analyzed for oxygen-isotope composition.

The average yield of the usable collagen samples was 7.1 ± 3.2%, with a range between 1.8 and 13.6%. The overall range and mean collagen yields are slightly higher than reported in previous studies from the area (Altun Ha – White, Pendergast et al. 2001; Chau Hiix – Metcalfe 2005, J. Metcalfe et al. 2009; Lamanai – Coyston et al. 1999; White and Schwarcz 1989; Marco Gonzalez and San Pedro – Williams 2000). However, the mean collagen yields reported in most of those studies include yields < 1%. There was no significant correlation between collagen yield and $\delta^{13}C$ values or $\delta^{15}N$ values when samples were subdivided by time period (Table 5.1-3), which suggests that the δ-values of these collagen samples have not been systematically altered by diagenesis.

The standard acceptable range for unaltered collagen C:N ratios is 2.9–3.6 (Ambrose 1990; DeNiro 1985; van Klinken 1999). The samples analyzed in this thesis all lie within

the expected range of C:N ratios (3.10 to 3.26; mean C:N = 3.18 ± 0.05). There was no significant correlation between C:N ratios and δ^{13}C values or δ^{15}N values when samples were subdivided by time period (Table 5.1-3).

Table 5.1-3 Collagen Correlation Tests

Test Correlation	Test Group	Result
Collagen Yield and δ^{13}C values	Postclassic	Pearson's r = –0.359, df = 11
	Historic	Pearson's r = 0.180, df = 11
Collagen Yield and δ^{15}N values	Postclassic	Pearson's r = –0.202, df = 24
	Historic	Pearson's r = 0.103, df = 24
C:N ratios and δ^{13}C values	Postclassic	Pearson's r = –0.192, df = 10
	Historic	Pearson's r = 0.058, df = 19
C:N ratios and δ^{15}N values	Postclassic	Pearson's r = –0.286, df = 10
	Historic	Pearson's r = 0.093, df = 19

5.2   Water

5.2.1   Results

Water samples from various sources at Lamanai were collected from May 2008 to June 2009 to inform the interpretation of the "local" baseline for water oxygen-isotope compositions (see section 4.5 for details and Appendix B for a complete list). The two major sources of drinking water available to the Lamaneros were the lagoon and shallow groundwater (e.g., natural freshwater springs). The δ^{18}O values of the lagoon and groundwater samples are shown in Figure 5.2-1 and Table 5.2-1. Groundwater δ^{18}O values from June and July are averages for multiple samples; data for spot samples from the other wells and freshwater springs are included. The June δ^{18}O value for the lagoon is also an average (n = 9) that includes samples taken from the lagoon, the outlet to the New River, and two small side creeks.

As discussed in section 3.1, Belize has distinct wet and dry seasons. This seasonality is apparent in the δ^{18}O values of the lagoon. The first water sample, May 2008, was taken at the end the dry season and has a high δ^{18}O value, reflecting that after partial evaporation the remaining liquid water is enriched in ^{18}O. There is then a lowering of
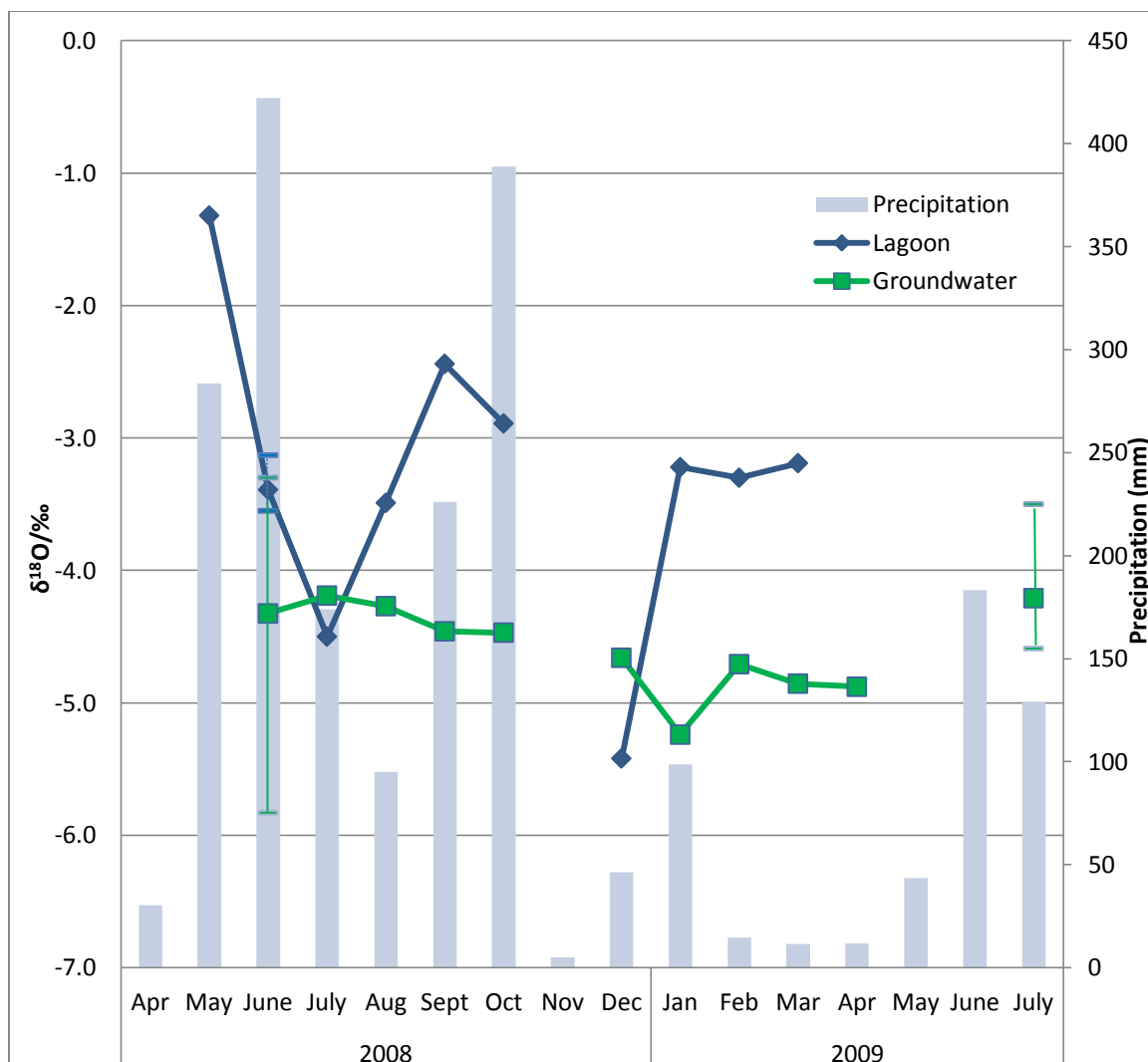
Figure 5.2-1 δ^{18}O values of water at Lamanai during 2008 and 2009 with associated precipitation. The error bars on the δ^{18}O values represent the range of values of the different samples taken in that category during the month.

δ^{18}O values that coincides with the beginning of the rainy season. The amount effect, which is the inverse correlation between the amount of rainfall and δ^{18}O, partially explains this drop. In Central America, the dominant control on the δ^{18}O value of precipitation is the amount effect; for every 100 mm increase in monthly rainfall, the precipitation δ^{18}O values decrease by 1.24 ‰ (Lachniet and Patterson 2009). Precipitation samples collected from Tropical Storm Arthur/Tropical Depression Alma (Table 5.2-1), for example, have very low δ^{18}O values, and it is heavy precipitation like this that drives down the lagoon's oxygen-isotope composition with the beginning of the

Table 5.2-1 $\delta^{18}O$ Values of Waters Sampled

Group	Description	Date Collected	$\delta^{18}O$ /‰	Notes
Lagoon	New River Lagoon	May-08	−1.3	
		Jun-08	−3.4	samples taken at various locations around the lagoon (−3.6 to −3.1 ‰; n = 9)
		Jul-08	−4.5	
		Aug-08	−3.5	
		Sep-08	−2.4	
		Oct-08	−2.9	
		Nov-08	n/a	sample not collected
		Dec-08	−5.4	
		Jan-09	−3.2	
		Feb-09	−3.3	
		Mar-09	−3.2	
Groundwater	Groundwater†	May-08	n/a	sample not collected
		Jun-08	−4.3	various well and spring samples (−5.8 to −3.3 ‰; n = 4)
		Jul-08	−4.2	
		Aug-08	−4.3	
		Sep-08	−4.5	
		Oct-08	−4.5	
		Nov-08	n/a	sample not collected
		Dec-08	−4.7	
		Jan-09	−5.2	
		Feb-09	−4.7	
		Mar-09	−4.9	
		Apr-09	−4.9	
		Jul-09	−4.2	spring samples (−4.6 to −3.5 ‰; n = 4)
Precipitation	Rainwater - Indian Church, Belize	May 25/08	−0.3	
		May 29/08	−1.3	
		May 30/08	−15.6	Tropical Storm/Depression‡
		May 30/08	−15.7	Tropical Storm/Depression‡
		June 2/08	−10.5	Tropical Storm/Depression‡
		June 10/08	−4.3	
		June 11/08	−3.9	
Other	Pond - Indian Creek*	May 17/08	−4.6	
	Tilapia Pond - Indian Church	June 12/08	−6.4	~ 1/2 way between Indian Church and San Carlos
	"Lake Ontario" - Indian Creek	June 13/08	−5.2	a large pond on the Weibe family property
	Jorge's Pond - Indian Creek	June 14/08	−4.2	

*Indian Creek is the Mennonite settlement closest to Lamanai

†Well-water unless otherwise noted

‡Precipitation associated with Tropical Storm Arthur/Tropical Depression Alma

rainy season. Figure 5.2-1 compares the $\delta^{18}O$ values of the lagoon and monthly precipitation, using data from the closest precipitation collection station (Tower Hill, Orange Walk). In 2008 there were two significant periods of rainfall, and correspondingly there are two large lowerings of $\delta^{18}O$ values.

Compared to the lagoon water oxygen-isotope compositions, the groundwater shows only minor fluctuations (Fig. 5.2-1), reflecting the averaging of precipitation recharge over time. There is still some fluctuation in $\delta^{18}O$ values that shows similar patterning to the lagoon - albeit attenuated and with a lag. There is a slight downward trend in the average groundwater $\delta^{18}O$ values from July 2008 to April 2009, reflecting precipitation recharge after Lamanai's rainy season had begun in earnest. By July of 2009, however, the groundwater oxygen-isotope composition returned to a similar value as July of the previous year, indicating a seasonal patterning similar to, but of lower amplitude than the lagoon.

Table 5.2-1 also presents oxygen-isotope data for precipitation events and opportunistic spot samples of surface water. These data help to illustrate the potential range of oxygen-isotope variation for drinking water, even within a single month. For example, while the drinking water from the lagoon in June 2008 was –3.4 ‰, Tropical Storm Arthur/Tropical Depression Alma precipitation yielded values as low as –15.7 ‰. However, single precipitation events would have limited impact on the oxygen isotopic composition of a bone forming over many years. Likewise, small ponds and isolated streams located away from the city centre would not be primary or even significant sources of drinking water for the majority of Lamanai's population. These spot samples also only represent one moment in time. Accordingly, the precipitation and spot samples were not included in the water oxygen-isotope averages for Lamanai.

The overall $\delta^{18}O$ average[34] for lagoon-associated water was –3.3 ± 1.1 ‰ (n = 11) and for groundwater, –4.6 ± 0.3 ‰ (n = 10). The lagoon's higher overall $\delta^{18}O$ is due to evaporation, as illustrated in Figure 5.2-2 (see Table 5.2-2 for corresponding data). Craig

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[34] The averages obtained for each month were used to calculate these values; n represents the number of months for which data were available.

(1961) demonstrated that the relationship between ^{2}H and ^{18}O in natural meteoric waters across the world that have not undergone excessive evaporation can be expressed by:

$$\delta^2H = 8\ \delta^{18}O + 10\ ‰\ ^{35}.$$

This meteoric water line is primarily a result of the equilibrium process of condensation. Water that has experienced evaporation (a combination of equilibrium and non-equilibrium processes) has a shallower slope. The Lamanai groundwater and the precipitation data fit very well ($r^2 = 0.9916$) along a local meteoric water line (LMWL) similar to the GMWL described by Craig (1961) (y = 7.7467x + 7.3151) whereas lagoon-
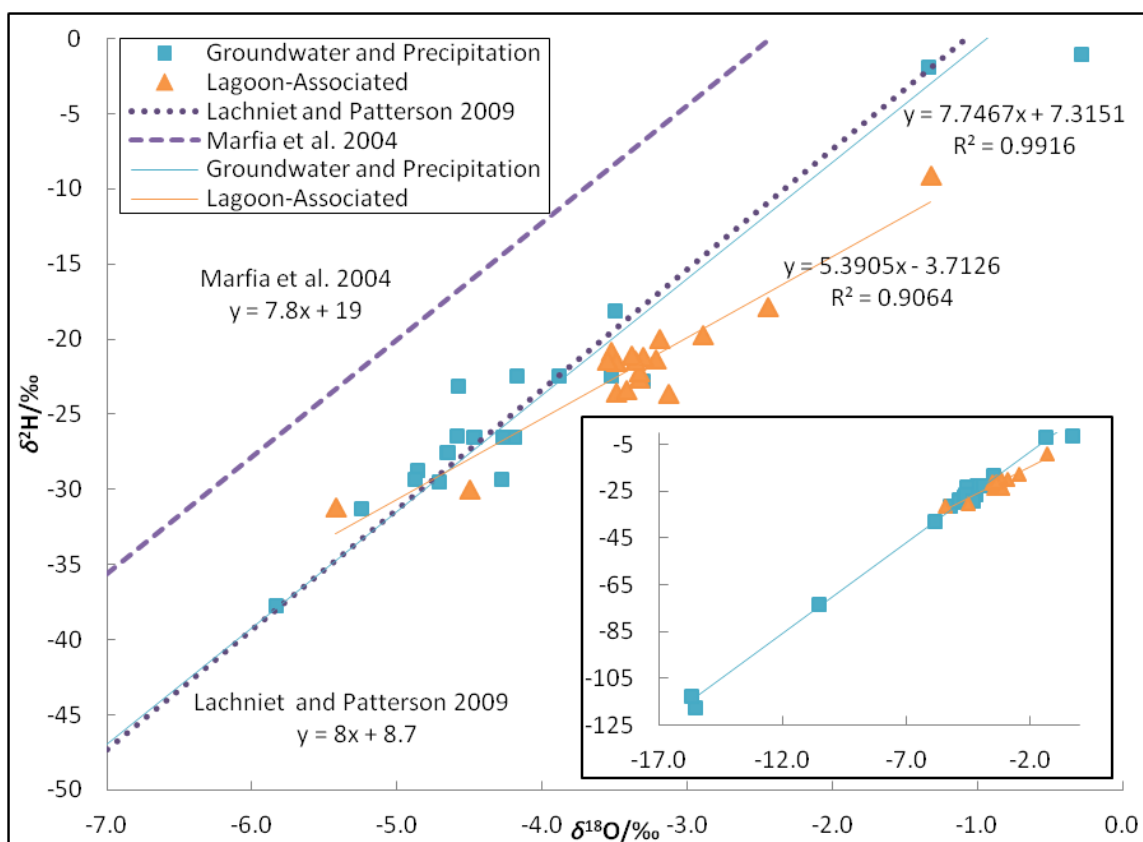
Figure 5.2-2 δ^2H and δ^{18}O values of Lamanai waters

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[35] This is referred to the Global Meteoric Water Line (GMWL). Local Meteoric Water Lines (LMWL) do vary from the GMWL due to the interplay of a variety of factors, such as water vapour source, average temperature, and relative humidity, as well as the amount of re-evaporation and transpiration occurring in the area.

Table 5.2-2 δ^2H and δ^{18}O Values of Lamanai's Groundwater, Precipitation, and Lagoon-Associated Waters

Group	Date Collected	Description	Average δ^{18}O/‰	Average δ^2H/‰
Lagoon-Associated Water	May 18/08	New River Lagoon (lake)	−1.3	−9
	June 13/08	New River Lagoon (lake)	−3.5	−21
	June 13/08	Barber Creek (endpoint)	−3.4	−23
	June 13/08	Barber Creek (midpoint)	−3.5	−22
	June 13/08	Barber Creek/New River	−3.3	−23
	June 13/08	"Marcus Creek" (endpoint)	−3.3	−22
	June 13/08	"Marcus Creek" (midpoint)	−3.4	−21
	June 13/08	"Marcus Creek"/New River	−3.1	−24
	June 13/08	New River Lagoon (lake)	−3.6	−21
	June 14/08	New River Lagoon (lake)	−3.4	−21
	Jul-08	Lagoon	−4.5	−30
	Aug-08	Lagoon	−3.5	−24
	Sep-08	Lagoon	−2.4	−18
	Oct-08	Lagoon	−2.9	−20
	Dec-08	Lagoon	−5.4	−31
	Jan-09	Lagoon	−3.2	−21
	Feb-09	Lagoon	−3.3	−21
	Mar-09	Lagoon	−3.2	−20
Groundwater & Precipitation	May 25/08	rain water	−0.3	−1
	May 29/08	rain water	−1.3	−2
	May 30/08	rain water	−15.6	−118
	May 30/08	rain water (Tropical Storm Arthur)	−15.7	−113
	June 2/08	rain water (Tropical Storm Arthur)	−10.5	−73
	June 4/08	Well 1	−3.5	−22
	June 4/08	Well 2	−5.8	−38
	June 10/08	rain water	−4.3	−29
	June 11/08	rain water	−3.9	−22
	June 12/08	fresh water spring	−3.3	−23
	June 14/08	Well 2	−4.7	−28
	Jul-08	Well 3	−4.2	−26
	Aug-08	Well 3	−4.3	−27
	Sep-08	Well 3	−4.5	−27
	Oct-08	Well 3	−4.5	−26
	Dec-08	Well 3	−4.7	−28
	Jan-09	Well 3	−5.2	−31
	Feb-09	Well 3	−4.7	−30
	Mar-09	Well 3	−4.9	−29
	Apr-09	Well 3	−4.9	−29
	July 5/09	spring flowing into lagoon	−3.5	−18
	July 5/09	spring	−4.2	−22
	July 5/09	spring	−4.6	−23
	July 5/09	spring	−4.6	−26

associated surface waters describe a line (local evaporation line) with a much shallower slope (y = 5.3905x − 3.7126; r² = 0.9064).

5.2.2   Other Belizean Water Isotopic Data

The modern mean annual oxygen-isotope composition of precipitation for Lamanai can be estimated using the Online Isotopes in Precipitation Calculator (OIPC) (Bowen 2013). This estimate is calculated from a global dataset using an algorithm developed by Bowen and Wilkinson (2002), Bowen and Ravenaugh (2003), and Bowen et al. (2005), and using data from the International Atomic Energy Agency and World Meteorological Organization Global Network for Isotopes in Precipitation. By inputting latitude, longitude, and altitude, the OIPC generated average δ^{18}O precipitation value for Lamanai was –4.6 ‰ (Bowen 2013). As the oxygen-isotope composition of precipitation is approximately equal to the oxygen-isotope composition of shallow groundwater (Sharp 2007), this study's average groundwater δ^{18}O value of –4.6 ‰ matches perfectly with the predicted results.

The average δ^{18}O values for groundwater and surface water also correspond well to the findings of other Belizean water studies. Marfia et al. (2004) obtained an average oxygen-isotope composition of –4.4 ‰ in their study of Belizean groundwater, and, as in this study, also found a higher average surface water δ^{18}O value of –3.9 ‰. Lachniet and Patterson's (2009) mid-dry season sampling of surface water in the general region of Lamanai yielded δ^{18}O values of ~ –4 to –3 ‰.

Lachniet and Patterson (2009) also defined a LMWL for Guatemala and Belize using data from non-evaporative surface water sources, which they previously demonstrated to be good proxies for precipitation δ^{2}H and δ^{18}O values in Central America (Lachniet and Patterson 2006). Their LMWL (δ^{2}H = 8.0 δ^{18}O + 8.7) is very similar to that measured here for Lamanai (Fig. 5.2-2). Using a combination of Belizean groundwater and surface water, Marfia et al. (2004) reported a LMWL of δ^{2}H = 7.8 δ^{18}O + 19. The slope of this LMWL is similar to that reported in this study, and by Lachniet and Patterson's (2009);

however, Marfia et al.'s (2004) d-intercept[36] and thus d-excess[37] or d is significantly higher. They suggest that the high d is the result of secondary continental vapor flux mixing with incoming vapor from the Caribbean Sea (Marfia et al. 2004). Lachniet and Patterson (2009), however, found no trend in d and rejected Marfia et al.'s (2004) claims of moisture recycling as a dominant factor controlling Belize water $\delta^{18}O$ values. The results obtained in this thesis are in agreement with Lachniet and Patterson (2009).

5.3 Phosphate-Oxygen Isotopic Data

Phosphate-oxygen isotope data were collected for 63 burials from 116 unique bone (n = 58) and tooth (n = 58) samples. The variations observed within these data will be explored first, before placing the $\delta^{18}O_p$ values into context of Lamanai's local baseline. Prior to interpretation of the results, adjustments were made to some tooth $\delta^{18}O_p$ values to account for the impact of breastfeeding[38], as discussed in section 2.3. To account for breastfeeding ^{18}O-enrichment, studies done in Mesoamerica suggest deciduous second molars and permanent first molars (M1s) be adjusted downward by 0.7 ‰, while a downward adjustment of 0.35 ‰ for premolars (PMs) and canines is recommended (White et al. 2000; White, Spence et al. 2004; White, Storey et al. 2004; White et al. 2007). In this study these adjustments were made to the tooth enamel $\delta^{18}O_p$ values in order to be consistent with other studies in the region. In the event that no explicit recommendations were made regarding corrections for a specific tooth type, no adjustments were made. It is acknowledged that these adjustments to $\delta^{18}O_p$ values are only approximate, as breastfeeding and weaning can be variable within a population and over time. In addition, if environmental water was added to the diet of the child during

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[36] The "d-intercept" of a water line reflects the source of water vapour and the conditions under which the vapour was formed (particularly humidity relative to saturation at sea surface temperature and wind speed, but it can also be affected by the incorporation of re-evaporated moisture). It represents the excess deuterium (^2H) that results from kinetic evaporative effects.

[37] Deuterium excess or d is defined as $d = \delta^2H - 8\,\delta^{18}O$

[38] Some studies also suggest making similar adjustments to bones of children ~ 3 and under, while leaving newborns/infants unadjusted as they reflect their mother's oxygen-isotope compositions (White, Longstaffe et al. 2004; White, Storey et al. 2004). A decision was made not to adjust the bone of the four individuals between 9 months and 2 years of age in this study. This lack of adjustment was kept in mind during relevant data interpretation (e.g., examining age differences in $\delta^{18}O_p$ values).

the weaning process, the degree of ^{18}O-enrichment would be reduced (Williams et al. 2005). However, it is not known when children were first introduced to water sources beyond breast-milk at Lamanai.

5.3.1   General Comparisons of $\delta^{18}O_p$ Values

5.3.1.1   Comparison of Tooth and Bone $\delta^{18}O_p$ Values

After the adjustments to the M1s, PMs, and canines (as discussed above), a paired t-test was used to evaluate the $\delta^{18}O_p$ values of all bone-tooth pairs[39] (n = 50). Even with the breastfeeding correction, there was still a statistically significant difference between tooth enamel and bone $\delta^{18}O_p$ values [t(49) = –4.707, p < 0.0005]. Teeth had generally (but not consistently) higher $\delta^{18}O_p$ values than bone with an average increase of 0.8 ± 1.1 ‰. The enamel – bone separation ($\Delta^{18}O_{p\ enamel-bone}$) ranged from –3.1 to +2.1 ‰. There are several explanations for this difference: metabolic differences in tissue formation, differences in water consumption patterns between children and adults, within-lifetime movement, and diagenesis.

The first possibility to consider is a metabolic difference in the formation of tissues. The bioapatite component of bone and enamel forms in equilibrium with body water. A metabolic difference in the formation of each tissue type could explain oxygen-isotope spacing between the two tissues, assuming that body water had the same isotopic composition when each tissue was forming. If this were the case, a relatively consistent $\Delta^{18}O_{p\ enamel-bone}$ would be expected. The lack of consistency in both the size and direction of the $\Delta^{18}O_{p\ enamel-bone}$ in this study does not lend itself to the idea of a metabolic difference in the formation of the different tissues. Other studies of coevally forming bone and tooth enamel also have not found consistent differences between enamel and

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[39] In all paired bone and tooth oxygen-isotope comparisons, as well as in all statistics where each individual should only be represented by one tooth data point, the breastfeeding-adjusted M1 was averaged with the M2 for N10-2/16 and N10-2/21 as the difference in $\delta^{18}O_p$ values is not very large. In the same situations, the utilized tooth enamel $\delta^{18}O_p$ value for N10-2/22 is an average of results for M1s taken from jaw A and jaw B as it was not clear which jaw belonged to the VPLF individual and there is < 0.1‰ difference between them. However, in general, for tooth enamel-only statistics the $\delta^{18}O_p$ values of both N10-2/22 A and B are used as they represent two separate individuals.

bone in phosphate-oxygen isotope compositions (Bellissimo 2013; Luz and Kolodny 1985; Emily C. Webb, personal communication).

Another explanation for the $\Delta^{18}O_{p\ enamel\text{-}bone}$ is differences in water consumption patterns between children and adults. These differences may not necessarily be consistent, accounting for individual variation in behaviours. Children (and possibly breastfeeding mothers, as the very young get a significant portion of their drinking water from breast-milk) may be drinking from different water sources (i.e., more evaporated water sources), or drinking from multiple sources in different proportions than the rest of the population (e.g., drinking more lagoon water than groundwater). Dietary water input could also be different between these two groups. As the mean difference in enamel to bone $\delta^{18}O_p$ values indicates an enrichment in ^{18}O of tooth over bone, it is possible that children are ingesting evaporated water in the form of more soups, stews, and heated beverages, etc. (Bretell et al. 2012).

As tooth enamel and bone (for the most part) represent two different times in an individual's life, difference in the oxygen-isotope composition between the two can also indicate within-lifetime movement. Although the mean $\delta^{18}O_p$ value of tooth enamel is higher than bone, this does not mean that everyone in this sample moved from an area with more ^{18}O-enriched drinking water to an area with less ^{18}O-enriched drinking water. The individual spacings of enamel to bone $\delta^{18}O_p$ values show significant variation in both size and direction (although 74% of the pairs have lower $\delta^{18}O_p$ values in bone than in tooth enamel). In addition, as discussed in section 2.3, a certain level of variability is expected within a population, and even within individuals. Only when the measured variability is larger than normal population variability can within-lifetime movement be reasonably posited. In Mesoamerica, the expected intrapopulational variability is ~ 2 ‰ (White et al. 1998; White et al. 2000; White, Spence et al. 2004; White, Storey et al. 2004). When an individual demonstrates higher variability in the oxygen-isotope spacing between their tooth enamel and bone, it is reasonable to assume within-lifetime movement.

Diagenesis is the last possibility considered here for the measured difference between bone and tooth $\delta^{18}O_p$ values. As bone is generally more susceptible to diagenetic alteration than tooth enamel, it is possible that the enamel $\delta^{18}O_p$ values are more reliable. However, as discussed in section 5.1, there was no evidence of post-mortem alteration using the generally accepted tests. An additional test is to investigate whether the lower bone $\delta^{18}O_p$ values are a result of bone-water interaction after burial. To explore this possibility, Zheng's (1996) hydroxyapatite-water oxygen-isotope thermometer can be used:

$$10^3 \ln\alpha = 3.83\ (10^6/T^2) - 6.48(10^3/T) + 2.05 \qquad \text{[Equation 5-1]}$$

where α is the ratio of $^{18}O/^{16}O$ in the hydroxyapatite to the $^{18}O/^{16}O$ in the water at equilibrium and T is the temperature in Kelvin. As discussed in section 2.2, bone mineral is commonly called hydroxyapatite; however, as bone composition often varies from the standard formula for hydroxyapatite, it is not identical. As such, the following calculations describe the trends related to temperature change, but do not provide actual $\delta^{18}O_p$ values.

During life, bone and its $\delta^{18}O_p$ values form at body temperature (37 ℃). Any material formed or exchanged after death would have $\delta^{18}O_p$ values that reflect environmental temperatures. Lamanai's average temperature is ~ 27 ℃[40]. Using Equation 5-1, the phosphate-water, oxygen-isotope $10^3 \ln\alpha$ for body temperature = 20.97 ‰, and for Lamanai's average temperature, 22.97 ‰. Using these calculated $10^3 \ln\alpha$ values and the following equation, the effect of temperature on $\delta^{18}O_p$ values can be determined:

$$10^3 \ln\alpha = 10^3 \ln[(10^3 + \delta_A)/(10^3 + \delta_B)]$$

where δ_A is the $\delta^{18}O_p$ value of bone and δ_B is the $\delta^{18}O$ value of water, –4.6 ‰. As discussed in section 5.2.1, this is both the average $\delta^{18}O$ value of Lamanai's modern groundwater and the estimated oxygen-isotope composition of precipitation. The resulting $\delta^{18}O_p$ (δ_A) values are +16.5 ‰ for hydroxyapatite formed at 37 ℃ ($10^3 \ln\alpha =$

[40] This is based on information from the Tower Hill weather station near in Orange Walk, the closest National Meteorological Service of Belize station to Lamanai.

20.97 ‰) and +18.5 ‰ for hydroxyapatite formed at 27 °C ($10^3 \ln\alpha = 22.97$ ‰). This demonstrates that bone $\delta^{18}O_p$ values should have increased rather than decreased if there was interaction with water after death at the average environmental temperature (assuming a constant $\delta^{18}O$ value for water). This suggests that post-mortem alteration of bone oxygen-isotope compositions by groundwater is unlikely to be the cause of the overall difference between bone and tooth $\delta^{18}O_p$ values.

In sum, the measured differences between tooth enamel and bone $\delta^{18}O_p$ values of the same individuals are not likely due to diagenetic change or metabolic differences in tissue formation. Difference in water consumption patterns between children and adults remains a possibility, as does intra-individual variability. However, in cases of large absolute enamel to bone $\delta^{18}O_p$ value spacings (~ 2 ‰ or more), within-lifetime mobility is a definite possibility. As there is a statistically significant difference between $\delta^{18}O_p$ values of bone and tooth enamel, and because these tissues generally represent insights into different points in an individual's life, the statistics of bone and tooth enamel oxygen-isotope compositions are dealt with separately in the following sections, unless discussing $\Delta^{18}O_{p\ enamel-bone}$.

5.3.1.2   Comparison of $\delta^{18}O_p$ Values by Time Period

Lamanai's overall average $\delta^{18}O_p$ value when the time periods are combined is +17.7 ± 0.8 ‰ (n = 58) for bone and +18.6 ± 0.9 ‰ (n = 56) for tooth enamel. In order to investigate the possibility of change in mobility over time, these data are subdivided into their respective time periods, the Postclassic or the Historic.

The Postclassic period bone has a higher mean $\delta^{18}O_p$ value (+18.0 ± 0.9 ‰, n = 31) than the Historic period bone (+17.4 ± 0.5 ‰, n = 27), and this mean 0.6 ‰ difference is statistically significant [t(49.213) = 2.866, p = 0.006]. The Postclassic also has a larger range than the Historic period (3.2 ‰ compared to 2.1 ‰), and the amount of variation between the two is significantly different [D'AD χ^2(1) = 7.798, p = 0.005], with the Postclassic having a more than 1.5 times larger coefficient of variation. Neither of the time periods, however, had any individuals that were identified as outliers (Fig. 5.3-1a). It is possible that the lower Historic period mean bone $\delta^{18}O_p$ value reflects a shift in

climate, possibly towards overall wetter conditions. It is also possible that the higher mean of the Postclassic period bone results in part from its larger variability, which could be a reflection of greater mobility (e.g., individuals accessing more ^{18}O-enriched water sources through travel).
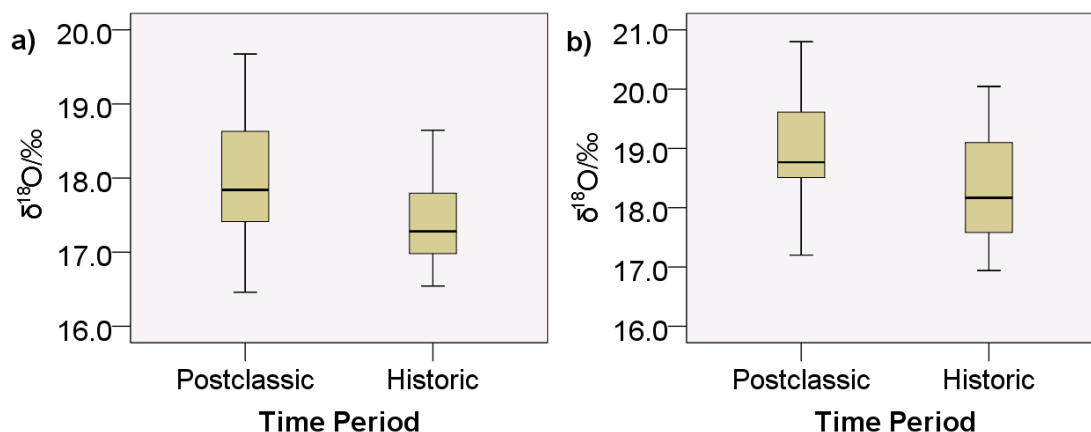
Figure 5.3-1 Boxplots of $\delta^{18}O_p$ values subdivided by time period: a) bone and b) teeth

The Postclassic period tooth enamel also has a higher mean $\delta^{18}O_p$ value (+18.9 ± 0.9 ‰, n = 32) than the Historic period (+18.3 ± 1.0 ‰, n = 24). The 0.6 ‰ difference is again statistically significant [t(54) = 2.379, p = 0.021], and there are no outliers in either time period (Fig. 5.3-1b). Since this difference between the two periods affects the oxygen-isotope compositions of both tissues similarly, it hints at change, which is discussed further in section 5.3.7.1.

5.3.1.3 Comparison of $\delta^{18}O_p$ Values by Sex

Based on previously made sex determinations of Lamanai's skeletal material, individuals were placed in one of five categories: Unknown, Male, Possible Male, Female, and Possible Female. Individuals whose sex determination appeared certain[41] were placed in

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[41] If the sex of an individual was listed with no comment (e.g., Male), for this study it was placed in that category (i.e., Male). If the sex had any commentary that suggested that the sexing was unsure (e.g., Possible Male, M?, ?M, etc.), the individual was placed in their respective "Possible" category (i.e.,

the corresponding Male or Female category. Only individuals assigned to the Male or Female categories are considered for the statistics exploring sex differences in this thesis.

When both time periods are considered together, the difference between the mean bone $\delta^{18}O_p$ value of males (+17.8 ± 1.0 ‰, n = 24) and females (+17.5 ± 0.6 ‰, n = 18) is not statistically significant [t(40) = 1.264, p = 0.214] and no outliers are identified for either sex (Fig. 5.3-2a). More variation is seen in male than female bone $\delta^{18}O_p$ values, demonstrated by their larger overall range (3.1 versus 2.3 ‰), interquartile range (1.6 versus 0.9 ‰), and standard deviation. This difference in variation is significant at the α = 0.10 level [D'AD $\chi^2(1)$ = 3.047, p = 0.081]. The observed difference in variation suggests that adult males were exposed to a wider variety of drinking water sources or had more adult mobility than females. Conversely, it appears that adult females were making use of or had access to a more restricted range of water sources than males.
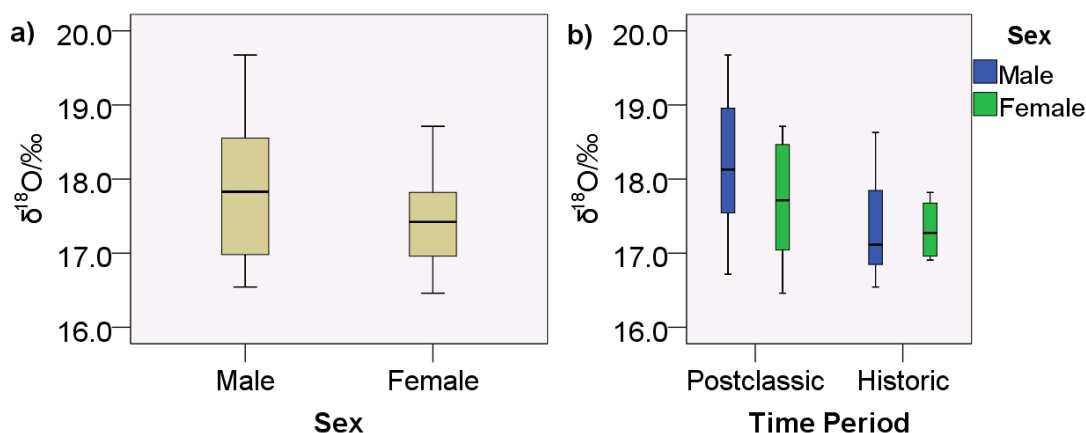
Figure 5.3-2 Boxplots of bone $\delta^{18}O_p$ values subdivided by a) sex and b) sex and time

These same patterns are not seen in the tooth enamel $\delta^{18}O_p$ values, as both sexes demonstrate a similar amount of variation. The difference in mean tooth $\delta^{18}O_p$ values between males (+18.6 ± 1.0 ‰, n = 24) and females (+18.4 ± 1.0 ‰, n = 17) is not

Possible Male or Possible Female). The individuals were assigned to the Unknown category when their sex was listed as "unknown" or none was determined by previous researchers.

statistically significant [t(39) = 0.482, p = 0.632] and no outliers are identified for either sex (Fig. 5.3-3a).
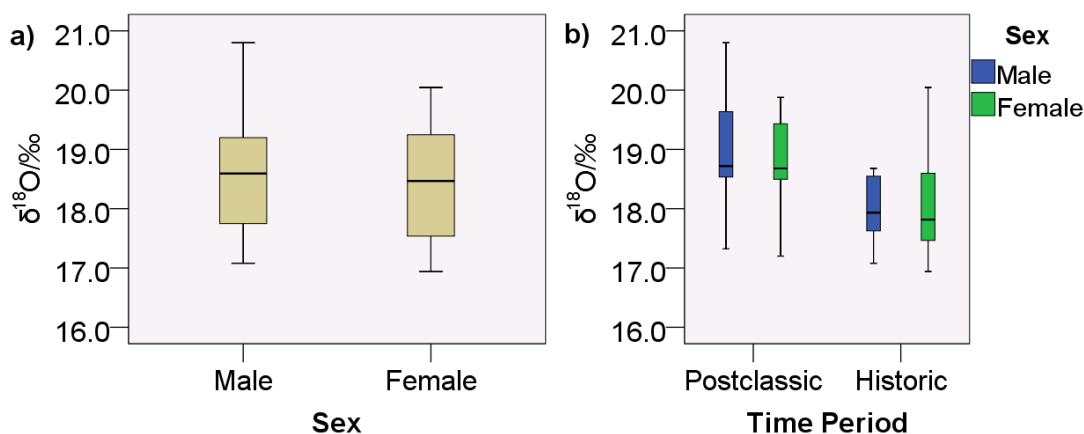
Figure 5.3-3 Boxplots of tooth $\delta^{18}O_p$ values subdivided by a) sex and b) sex and time

5.3.1.4   Comparison of $\delta^{18}O_p$ Values by Age

Individuals were initially divided into three categories based on age at death: Juvenile, Young Adult, and Adult. Juvenile includes any individuals who were estimated to be younger than 10 years of age, or if the majority of their potential age range was younger than 10 years (i.e., an individual assigned an estimate of 6–12 years would be considered a Juvenile, whereas an individual given an age range of 9–13 years would be placed in the next category). Young Adults are individuals between ~ 10 and 20 years of age, and Adults are individuals ~ 20 years and older.

Bone phosphate-oxygen isotope compositions were examined using the above divisions. Given the existing age distribution of individuals between and within time periods and the possibly confounding effect of time, comparisons between age groups of the sample as a whole are not appropriate.

Tooth $\delta^{18}O_p$ values were grouped on the basis of tooth type[42], as each tooth type represents a specific age range of an individual's life (Table 2.2-1), although there is some overlap between groups[43]. Table 5.3-1 presents descriptive statistics for each tooth type; the M1s have the lowest values of all of the groups. The largest difference between the mean $\delta^{18}O_p$ values of the different tooth types is the –1.4 ‰ mean difference between the M1s and the permanent second molars (M2s).

Table 5.3-1 Mean $\delta^{18}O_p$ Values of Each Tooth Type Grouped and Subdivided by Time

Time Period	Tooth Type	Age	Mean $\delta^{18}O_p$/‰	n	Std. Deviation	Min.	Max.
	Deciduous	in utero to < 9 mos	19.3	5	.4	18.8	19.7
	M1	birth to 2.5–3 yr	18.4	42	.9	16.9	20.2
	M2	2.5–3 to 7–8 yr	19.8	7	.6	18.8	20.8
	PM	1.5 to 7 yr	18.9	4	.7	16.9	19.6
Postclassic	Deciduous	in utero to < 9 mos	19.0	3	.3	18.8	19.4
	M1	birth to 2.5–3 yr	18.6	22	.8	17.2	20.2
	M2	2.5–3 to 7–8 yr	19.8	6	.6	19.8	20.8
	PM	1.5 to 7 yr	19.2	3	.5	18.6	19.6
Historic	Deciduous	in utero to < 9 mos	19.7	2	.1	19.6	19.7
	M1	birth to 2.5–3 yr	18.1	20	.9	16.9	20.1
	M2	2.5–3 to 7–8 yr	19.7	1	—	—	—
	PM	1.5 to 7 yr	17.9	1	—	—	—

This difference could be a result of the discrepancy in the sample size between the two tooth types as there are six times as many M1s as M2s. Several of the M2-represented individuals may not have spent their childhood (between ages ~ 2.5 to 8 years) accessing the same water sources as most of the M1 individuals were during the first few years of their life. It is also possible that part of the difference between the two is related to a breastfeeding effect in the M2s. As will be discussed in section 5.4, breastfeeding can be variable within a society, and some individuals may have still been being breastfed

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[42] In situations where there is an M1 and an M2 belonging to the same individual, both are included in their own category. Even if the teeth belonging to these individuals were excluded, the overall results would be the same.

[43] As there were few deciduous teeth in total and two types represented by only a single individual, these were grouped together under the "Deciduous" heading. This group spans from 13 weeks in utero to 9 months. There is some overlap between these and first molars' age range of birth to 2.5/3 years of age. Premolars' range of 1.5/2 to 7/8 years overlaps with both M1s and M2s (2.5/3 to 7/8 years).

during the beginning of the formation of their M2s, but unlike the M1s (and the PMs) no adjustment was made for this possibility.

5.3.2 $\delta^{18}O_p$ Comparisons – Postclassic Period

5.3.2.1 Comparison of $\delta^{18}O_p$ Values by Sex

In the Postclassic period sample, males have a mean bone $\delta^{18}O_p$ value of +18.2 ± 1.0 ‰ (n = 13), which is not statistically different from the female's mean of +17.7 ± 0.8 ‰ (n = 8) [t(19) = 1.274, p = 0.218]. Neither males nor females had identifiable bone outliers; however, males have a slightly larger overall range (Fig. 5.3-2b) and standard deviation. There is no difference in the mean tooth $\delta^{18}O_p$ values of males (+18.9 ± 1.0 ‰, n = 15) and females (+18.8 ± 0.9 ‰, n = 7). No outliers were identified for either sex (Fig. 5.3-3b).

5.3.2.2 Comparison of $\delta^{18}O_p$ Values by Age

When bone $\delta^{18}O_p$ values from the Postclassic period are subdivided by age at death into three categories, Juveniles have a slightly lower mean $\delta^{18}O_p$ value than the older age groups; however, even Juvenile outliers N10-2/50 and N10-9/2 are inside the Adult range (Table 5.3-2).

Table 5.3-2 Mean $\delta^{18}O_p$ Values of Bone in Each Time Period Subdivided by Age

Time Period	Age	Mean $\delta^{18}O_p$/‰	n	Std. Deviation	Min.	Max.
	Juvenile	17.6	5	0.6	16.7	18.4
	Young Adult	18.3	3	1.1	17.6	19.5
Postclassic	Adult	18.1	23	1.0	16.5	19.7
	Juvenile	17.9	4	0.6	17.2	18.7
Historic	Adult	17.3	23	0.5	16.5	18.6

When the Postclassic tooth $\delta^{18}O_p$ values are subdivided by tooth type, as with the whole sample, the largest difference in means is between the M1s (birth to 2.5/3 year olds) and the M2s (2.5/3 to 7/8 year olds) (Table 5.3-1). As discussed in section 5.3.1, this difference may, in part, be due to a breastfeeding effect. Alternatively, several of the individuals from whom M2s were selected might have had overall higher $\delta^{18}O_p$ values

that were not specifically age related. For example, the M2s of N10-2/16 and N10-2/21, which have higher $\delta^{18}O_p$ values than the M1 average, have M1s with slightly higher $\delta^{18}O_p$ values than their M2s. N10-4/26, another sample with high M2 $\delta^{18}O_p$ values, has a near-identical bone $\delta^{18}O_p$ value, meaning that the water sources this 30+ year-old man consumed between 2.5/3 and 7/8 years of age were similar in oxygen-isotope composition to those he consumed during his last years.

5.3.2.3   Comparison of $\delta^{18}O_p$ Values by Structure Type

Burials at Lamanai have been found both in structures used for ceremonial purposes and those used for residential and/or administrative functions. When the individuals are subdivided by burial structure type, there is no significant difference in mean bone $\delta^{18}O_p$ values between ceremonial (+17.9 ± 0.8 ‰, n = 14) and residential/administrative (+18.1 ± 1.0 ‰, n = 17) structures [t(29) = –0.404, p = 0.689]. There is also no difference between mean tooth $\delta^{18}O_p$ values of burials in ceremonial (+18.7 ± 0.8 ‰, n = 14) and residential/administrative (+19.0 ± 0.9 ‰, n = 16) contexts [t(28) = –0.867, p = 0.394]. However, each structure type had a range of tooth $\delta^{18}O_p$ values closer to 3 ‰ than the 2 ‰ expected for intrapopulational variability in Mesoamerica. Thus, it is possible that there are individuals within each structure type who did not spend portions of their childhood in the same location as each other.

5.3.3 $\delta^{18}O_p$ Comparisons – Historic Period

5.3.3.1   Comparison of $\delta^{18}O_p$ Values by Sex

In the Historic period, there is essentially no difference in the mean bone $\delta^{18}O_p$ values of males (+17.3 ± 0.7‰, n = 11) and females (+17.3 ± 0.4‰, n = 10) [t(19) = 0.010, p = 0.992]. Although there are no outliers for either sex, males do have a much larger overall range (3.2 ‰ compared to 2.1 ‰), as well as a slightly larger interquartile range (Fig. 5.3-2b) and standard deviation.   This variation is significant at the α = 0.10 level [D'AD $\chi^2(1)$ = 2.802 p = 0.094]. This suggests that adult males had access to a wider variety of water resources than adult females, possibly through travel or relocation.

Such high variability is not apparent in the tooth enamel oxygen-isotope compositions for males. Instead, during infancy/childhood, it is the females with a much larger range of enamel $\delta^{18}O_p$ values. At 3.1 ‰, this range is almost twice the size of the males' 1.6 ‰ range. However, there is no difference in the mean tooth $\delta^{18}O_p$ values of males (+17.9 ± 0.6 ‰, n = 9) and females (+18.1 ± 1.0 ‰, n = 10) [t(17) = –0.494, p = 0.628], and there are no outliers for either sex (Fig. 5.3-3b). Nonetheless, the larger range of tooth $\delta^{18}O_p$ values for females suggests that not all of them were born and/or spent their childhood in the same location.

5.3.3.2   Comparison of $\delta^{18}O_p$ Values by Age

Only Juveniles and Adults are represented in the Historic period sample. While Juveniles have a slightly higher mean bone $\delta^{18}O_p$ value (Table 5.3-2), their values almost all fit within the Adult range. Due to the limited number of non-M1s sampled from the Historic period, meaningful conclusions regarding differences in age groups represented by tooth types could not be drawn (Table 5.3-1).

5.3.3.3   Other Variations in $\delta^{18}O_p$ Values

As presented in section 5.3.1, Historic period bone has a mean $\delta^{18}O_p$ value of +17.4 ± 0.5 ‰ (n = 27), and tooth enamel has a mean $\delta^{18}O_p$ value of +18.9 ± 0.9 ‰ (n = 32). When compared, there is statistically greater variation in tooth than bone $\delta^{18}O_p$ values [D'AD $\chi^2(1) = 6.608$ p = 0.010]. The difference in variability between the tissues suggests that there was more variation in individuals' childhood water resources than in those being consumed over the years leading up to death. Perhaps there was more variability in individuals' origins than in their locations during the latter years of their life.

5.3.4   Within-Lifetime Variability

In the preceding sections, bone and tooth oxygen-isotope compositions of the same individuals were dealt with separately. In the following section they are considered in relation to each other as pairs. As explained in section 5.3.1, having ruled out diagenesis and metabolic factors, within-lifetime movement is a way to explain the spacing between tooth and bone $\delta^{18}O_p$ values, particularly when it is ≥ ~ 2 ‰ within an individual. While

differences in water consumption patterns between adults and children remains a possibility, it is not the likeliest explanation for the larger spacings. In the following section, it is posited that the differences seen in spacings between tooth and bone $\delta^{18}O_p$ values are caused, at least in part, by mobility.

5.3.4.1   Individual Differences in $\delta^{18}O_p$ Values

The bone and enamel $\delta^{18}O_p$ values of each individual are compared in Figure 5.3-4. The average absolute difference between individual enamel and bone $\delta^{18}O_p$ values ($|\Delta^{18}O_p$ $_{enamel\text{-}bone}|$) was 1.2 ‰ (range = 0.0 ‰ to 3.1 ‰). Methodological error can account for an absolute difference of up to ~ 0.5 ‰ in $\delta^{18}O_p$ values (see section 4.2). For individuals whose $|\Delta^{18}O_p$ $_{enamel\text{-}bone}|$ falls below this 0.5 ‰ cut-off, it is not possible to say that their bone and tooth $\delta^{18}O_p$ values are different. Assuming that differences between tooth and bone in part reflect within-lifetime movement, such individuals are least likely to have moved. Out of the 50 bone-tooth pairs there are 11 individuals who fall into this category (see Fig. 5.3-4), and they include individuals from both time periods and both sexes. That said, archaeological sites are not always distinct from one another in their water oxygen isotopic composition. Individuals who appear not to have moved based on their small $|\Delta^{18}O_p$ $_{enamel\text{-}bone}|$ may still have relocated between locations where the drinking water has similar isotopic compositions.

Individuals with large $|\Delta^{18}O_p$ $_{enamel\text{-}bone}|$ likely did move between locations with differing oxygen-isotope compositions of drinking water. As discussed previously, in Mesoamerica intrapopulational variability is expected to be ~ 2 ‰ (White et al. 1998; White et al. 2000; White, Spence et al. 2004; White, Storey et al. 2004). There are seven individuals (Fig. 5.3-4) with $|\Delta^{18}O_p$ $_{enamel\text{-}bone}| \geq 2.0$ ‰, and as such are most likely to have experienced within-lifetime movement. Three of these individuals will be discussed in the following paragraphs as they have the most anthropological significance.

One of these individuals, N11-5/7A, is a Postclassic period male ~ 40–50 years old with an enamel $\delta^{18}O_p$ value similar to the population mean, but one of the entire sample's lowest bone $\delta^{18}O_p$ values. What is more interesting is that the individual buried with him,
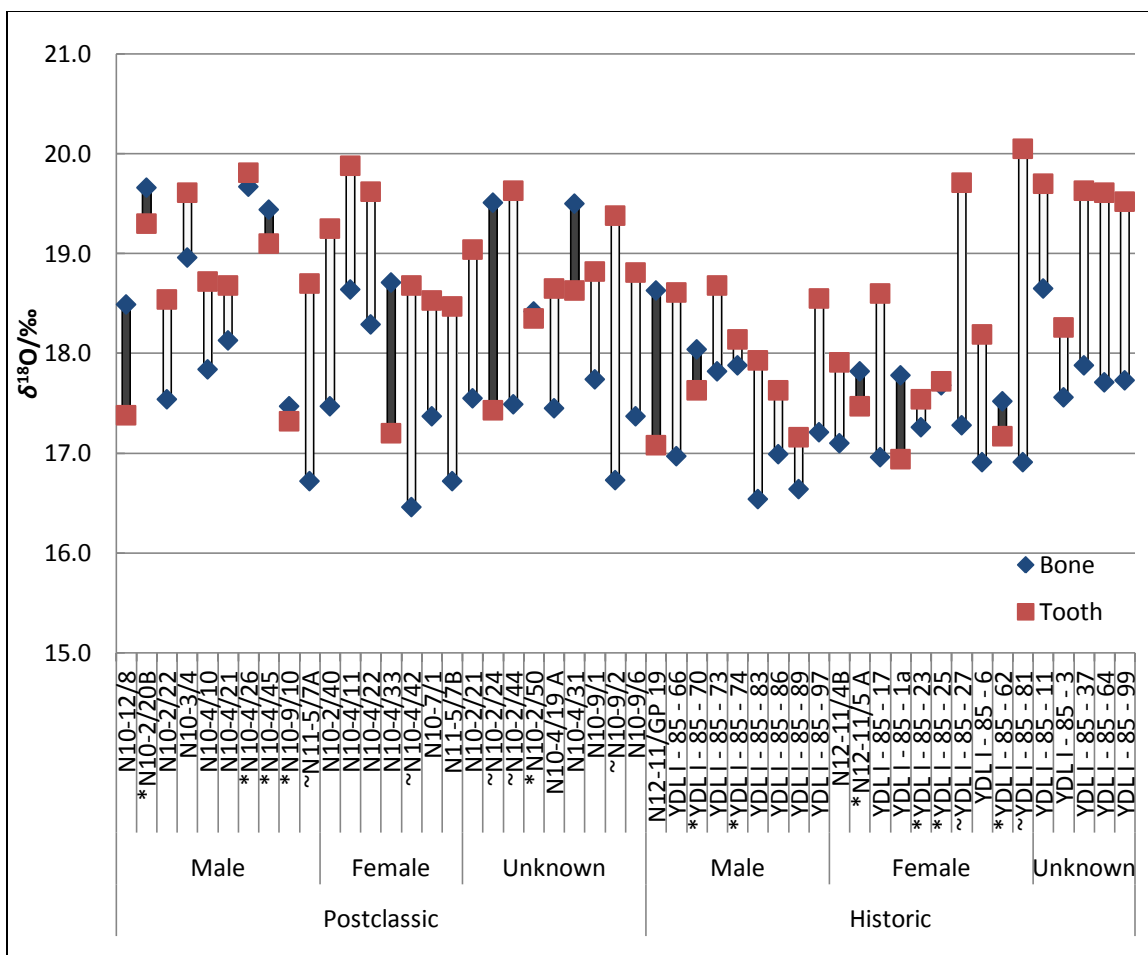
Figure 5.3-4 $\delta^{18}O_p$ values of bone and tooth pairs organized by time period and sex. Individuals who are least likely to have moved are marked with as asterisk (*). Individuals who are most likely to have experienced within lifetime movement are marked with a tilde (~).

N11-5/7B, also demonstrates a similar shift in $\delta^{18}O_p$ values[44] (Fig. 5.3-4). Both appear to have spent the first 2.5 to 3 years of life accessing isotopically similar water sources and then, at some point, began drinking less ^{18}O-enriched water. N11-5/7B is an adult female ~ 20–25 years old. A joint burial may indicate some sort of relationship or connection between the deceased, whether it be a real social/familial relationship or merely a similar time of death. These individuals are "The Loving Couple" discussed in

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[44] N11-5/7B's $|\Delta^{18}O_{p\ enamel-bone}|$ is only 1.8 ‰, which is why she did not appear on the original list of individuals most likely to have moved.

Pendergast (1989) and White et al. (2009), so named for their placement in the burial with the woman's arm around the man's shoulders. This unique expression of affection in the burial and the similarity in their oxygen-isotope compositions at both life stages supports an in-life connection.

The individual with the largest absolute difference between her tooth enamel and bone $\delta^{18}O_p$ values is YDL-85-81, a Historic period female ~ 35–50 years old. With a $|\Delta^{18}O_p$ enamel-bone$|$ of 3.2 ‰, she likely relocated during her lifetime. As was mentioned briefly in section 5.3.3, there is significant evidence of Historic period female mobility – particularly when compared to temporally equivalent males. The only other Historic individual from the sample identified as most likely to have experienced within-lifetime movement is also a female (YDL-85-27). If the isotopic cut-off for candidates for within-lifetime movement was lowered by 0.1 ‰ the only other addition would be another Historic individual, YDL-85-64, who was also tentatively identified as a female.

5.3.4.2   Variation in $|\Delta^{18}O_{p\ enamel\text{-}bone}|$

When absolute difference in tooth enamel and bone $\delta^{18}O_p$ values are subdivided by time period, no difference exists between the Postclassic (1.2 ± 0.7 ‰, n = 26) and the Historic periods (1.1 ± 0.8 ‰, n = 24). A subdivision by sex reveals a female mean $|\Delta^{18}O_{p\ enamel\text{-}bone}|$ of 1.3 ± 0.8 ‰, which is ~ 0.5 ‰ higher than the males' spacing of 0.8 ± 0.5 ‰. However, the sexed groups' $|\Delta^{18}O_{p\ enamel\text{-}bone}|$ are not significantly different [U^{45} = 214, z = 1.664, p = 0.100], unless they are first also subdivided by time period.

In the Postclassic period, females show much larger and statistically significant differences between tooth enamel and bone $\delta^{18}O_p$ values than males (Fig. 5.3-5a; female $\bar{x}$ = 1.6 ± 0.4 ‰, n = 7; male $\bar{x}$ = 0.8 ± 0.6 ‰, n = 10) [U = 64, z = 2.830, p = 0.005]. Relative to males, they demonstrate a greater difference in water sources ingested in childhood compared to adulthood. This could indicate that females experienced more within-lifetime mobility than males, or that their within-lifetime movements involved

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[45] For exploring the difference in $|\Delta^{18}O_{p\ enamel\text{-}bone}|$ between groups the Mann-Whitney U test is used instead of its parametric counterpart (t-test) due to concerns arising from violations of assumptions.

travel between areas that are more climatically and/or physiographically different. There are no Postclassic females that unambiguously experienced no change in their water sources between childhood and adulthood, as the smallest female $|\Delta^{18}O_{p\ enamel-bone}|$ is 1.2 ‰. Relative to females, males exhibit more variability in $|\Delta^{18}O_{p\ enamel-bone}|$ [D'AD $\chi^2(1)$ = 4.090, p = 0.043], ranging from essentially 0 to 2.0 ‰ (N11/5-7A), the latter likely indicating within-lifetime movement.

In the Historic period, such differences between the sexes are not present (Fig. 5.3-5b). The mean $|\Delta^{18}O_{p\ enamel-bone}|$ for females (1.1 ± 1.0 ‰, n = 10) and males (1.0 ± 0.5 ‰, n = 9) are the same, and the difference in variation between the sexes' $|\Delta^{18}O_{p\ enamel-bone}|$ is not statistically significant [D'AD $\chi^2(1)$ = 0.958 p = 0.328]. Therefore, the almost complete separation by sex using $|\Delta^{18}O_{p\ enamel-bone}|$ is only characteristic of the Postclassic period dataset.
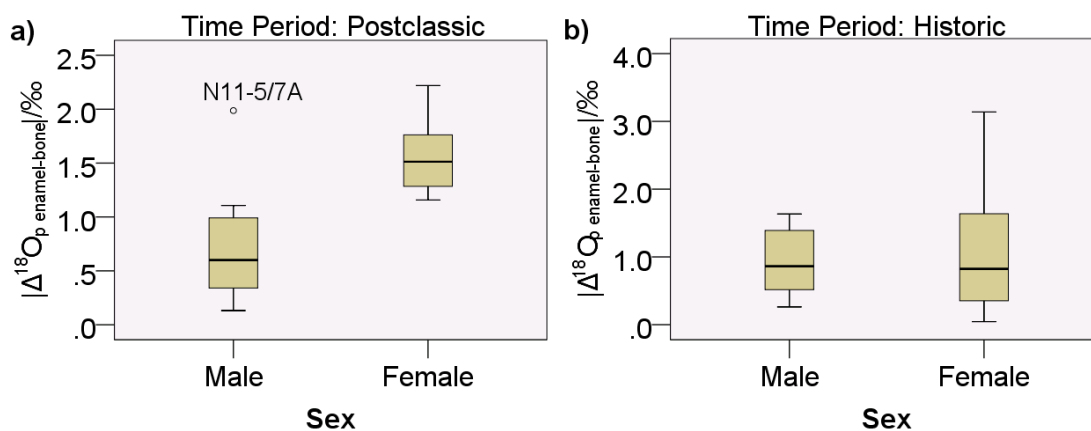
Figure 5.3-5 Boxplots of distribution of $|\Delta^{18}O_{p\ enamel-bone}|$ by time period in the a) Postclassic period and b) Historic period

One should be reminded that all of the $|\Delta^{18}O_{p\ enamel-bone}|$ values discussed above are small. Most of the mobility in this sample (assuming $|\Delta^{18}O_{p\ enamel-bone}|$ indicates within-lifetime movement) probably occurred between geographically proximal areas with similar water isotopic compositions.

5.3.5 Lamanai Local Oxygen Isotope Baseline

To determine whether or not an individual's $\delta^{18}O_p$ value is local[46], it is important to establish a local baseline. For archaeological studies, there are two main ways to do so. The first is to use estimates or knowledge of the oxygen-isotope composition of local drinking water sources (making the assumption that there has not been significant climatic change in the area over time), and then use a calculation to convert these potential drinking water compositions to bone phosphate-oxygen isotope values. The second option is to use previously established baselines for local, or relatively local, coeval burial populations. At Lamanai, it is possible to use both of these approaches.

5.3.5.1 Modern Water Samples

As presented in section 5.2, the water samples collected for this study produced an overall average oxygen-isotope composition for lagoon water of −3.3 ‰ and a groundwater average of −4.6 ‰. There are several equations available to convert these isotopic compositions to those expected for associated bioapatite phosphate-oxygen (i.e., Longinelli 1984; Luz et al. 1984; Levinson et al. 1987; Daux et al. 2008). There is no general agreement over which of these equations is most appropriate to use (Chenery et al. 2010; Chenery et al. 2012), but the differences in results among the approaches is generally not large. The equation of Daux et al. (2008), which is built on all of the earlier work, is employed here:

$$\delta^{18}O_p = (\delta^{18}O_w - 33.72) / 1.54 \qquad \text{[Equation 5.2]}$$

Equation 5.2 produces an $\delta^{18}O_p$ value of +19.8 ‰ using average lagoon water and +18.9 ‰ using average groundwater.

5.3.5.2 Baselines from Previous Studies

Howie et al. (2010) suggested a baseline for Lamanai using structural carbonate oxygen-isotope data ($\delta^{18}O_{sc}$, +26.3 to +28.5 ‰). This baseline is based on results for individuals

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[46] Local in this case meaning that the individual spent most of the time period represented by the examined tissue ingesting water whose oxygen isotopic composition was consistent with that being consumed in the area of interest.

interred in the Ottawa complex, the likely residence of the site's ruling elite. These individuals showed the highest degree of "locational stability" in their bone-enamel pairs and low inter-individual variability compared to the other groups in the study. This baseline is not directly comparable with the water baselines or the $\delta^{18}O_p$ data presented here. There is, however, a close relationship between carbonate- and phosphate-oxygen isotopic compositions in mammals (Bryant et al. 1996; Iacumin et al. 1996; Chenery et al. 2012). Because there is some internal and inter-species variability (Martin et al. 2008; Pellegrini et al. 2011), Chenery et al.'s (2012) equation was used as it is based on human material. Using the Chenery et al. (2012) equation:

$$\delta^{18}O_p = 1.0322 \text{ x } \delta^{18}O_{sc} - 9.6849$$

the Howie et al. (2010) baseline becomes +17.5 to +19.7 ‰, which is in general agreement with the preliminary, less selective, $\delta^{18}O_p$-data based bone and enamel "baselines" by White et al. (2009). The Howie et al. (2010) converted range is the baseline for Lamanai used in this study.

Phosphate-oxygen isotope baselines have also previously been established for the nearby sites of Altun Ha (~ 40 km east of Lamanai) and Chau Hiix (approximately half-way between Altun Ha and Lamanai) (Olsen 2006; Metcalfe 2005). These sites are also climatically and physiographically similar to Lamanai. The Howie et al. (2010) converted baseline compares well with the $\delta^{18}O_p$ values established for both these lowland sites (Table 5.3-3).

5.3.5.3   Fit of the Local Baseline

The calculated $\delta^{18}O_p$ value of +18.9 ‰ established by modern groundwater sampling fits within the top half of the Howie et al. (2010) baseline range (Fig. 5.3-6). However, the $\delta^{18}O_p$ value of +19.8 ‰ calculated from the isotopic composition of the modern lagoon lies just above the upper range of the Howie et al. (2010) Lamanai baseline, which might suggest that water sources impacted by evaporation (like the lagoon) made up a less significant portion of the community's drinking water than did groundwater. It should be

noted that the modern water values only represent one year of sampling (capturing only a portion of the inter-annual variation that may be present at the site).

Table 5.3-3 $\delta^{18}O_p$ Values for Mesoamerican Sites

Site	Mean $\delta^{18}O_p$ /‰	Std. Deviation	n	Min.	Max.	General Location
Altun Ha	18.9	0.8	18	17.7	20.0	Lowland Coastal Belize
Chau Hiix	18.8	0.8	11	17.2	19.6	Lowland Belize
Ixchimché	15.7	0.4	2	15.4	16.0	Guatemalan Highlands
Kaminaljuyú	16.7	0.7	30	15.6	17.7	Guatemalan Highlands
Monte Alban	13.0	0.6	16	12.1	13.9	Valley of Oaxaca, Mexico
Rio Azul/Rio Bravo	19.9	0.7	7	18.3	20.4	Lowland Northeastern Guatemala
Teotihuacan	14.8	0.3	11	14.3	15.2	Basin of Mexico
Guanajuato/Lake Zacapu sites[*†]	14.3			13.5	15.0	Michoacan (West Mexico)
Lake Patzquaro sites[*‡]	12.8			12.1	13.7	Michoacan (West Mexico)

Source: Data from Metcalfe 2005; Olsen 2006; White et al. 1998; White, Longstaffe, and Law 2001; White, Storey et al. 2004; White et al. 2009.

[*] Estimated from White et al. 2009, figure 7.2.

[†] Includes Tzintzuntzan, Urichu, Tocuaro, Atoyac, and Teremondo.

[‡] Includes Portales, Guadalupe, Los Nogales, Palacio, and Milpillas.

Both the average bone and tooth $\delta^{18}O_p$ values fall within the baseline range determined by Howie et al. (2010), as do more than two-thirds of the individual samples. Of the samples that lie outside of the baseline range, the majority (84%) have lower $\delta^{18}O_p$ values. By time period (Fig. 5.3-6), the Howie et al. (2010) baseline better fits the Postclassic data than the Historic period results. The average $\delta^{18}O_p$ value of Historic period bone falls just below the lower end of the baseline range. As discussed in section 5.3.1, there is a decrease of ~ 0.6 ‰ in both the bone and tooth $\delta^{18}O_p$ values from the Postclassic to the Historic period. As the Howie et al. (2010) baseline is based on Terminal Classic and Early Postclassic individuals, its better fit to this study's Postclassic data is likely due to the overlap in time periods. As mentioned in section 5.3.1, there is the possibility that climate change affected drinking water isotopic compositions at Lamanai. There is even evidence to suggest that climate change occurred between the Terminal Classic/Early Postclassic and the rest of the Postclassic period (e.g., Medina-Elizande and Rohling 2012; see section 5.3.7.1), which may help to explain why the

Howie et al. (2010) baseline is not a more perfect fit for the Postclassic data. Higher $\delta^{18}O_p$ values would be expected in the Terminal Classic/Early Postclassic period droughts than in the wetter conditions that followed.
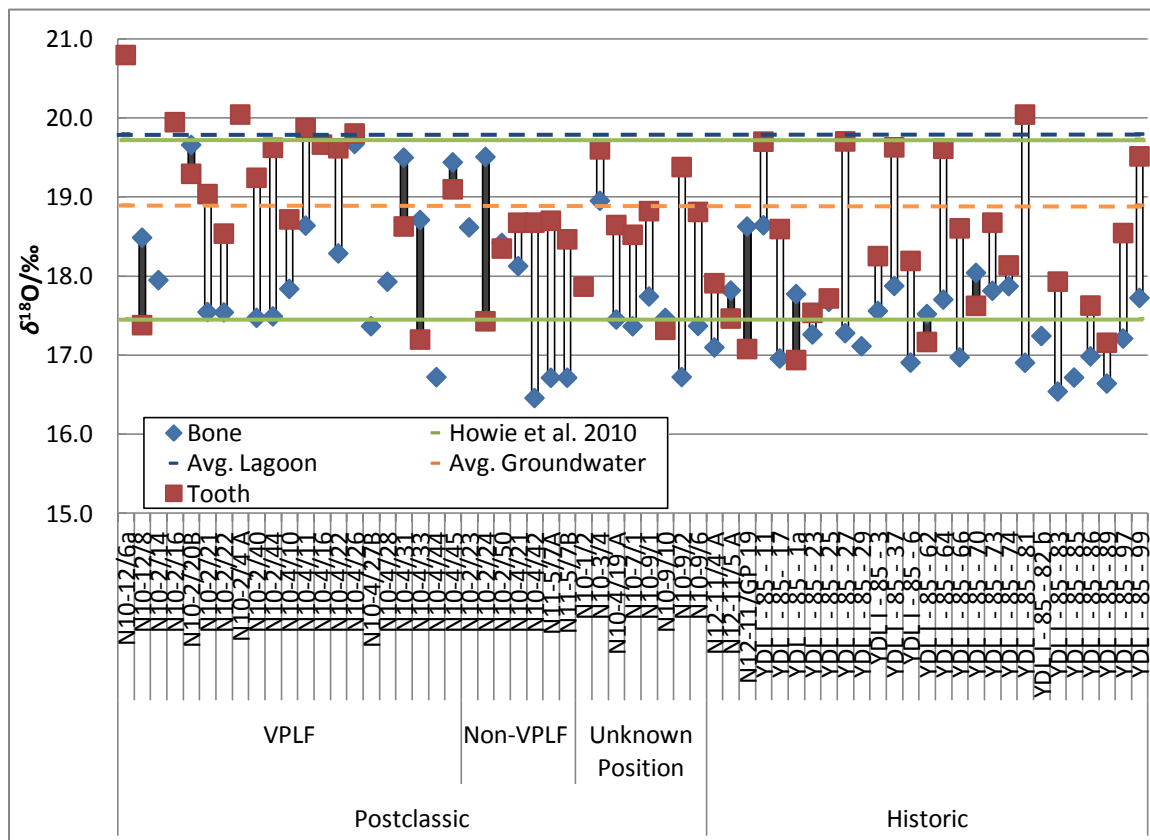
Figure 5.3-6 Bone and tooth $\delta^{18}O_p$ values of all individuals in this study. The $\delta^{18}O_p$ value for average lagoon water is +19.8 ‰, the average groundwater is +18.9 ‰, and the Howie et al. (2010) Lamanai baseline is +17.5 to +19.7 ‰.

5.3.5.4   Using the Baseline to Identify Non-Locals at Lamanai?

Along with the possibility that climate fluctuations through time caused some samples to fall outside of the established baseline range, there is also the possibility that some of these $\delta^{18}O_p$ values represent non-local individuals. The difficulty with this dataset is that the $\delta^{18}O_p$ values are continuous with almost no identifiable outliers.

The region surrounding Lamanai is climatically and physiographically relatively uniform, which makes mobility within the region difficult to identify. The entire northern half of

Belize is classified as a "dry tropical" zone with a relatively similar temperature and amount of precipitation (Wright et al. 1959). Spatially, distance from the Caribbean coast (as a result of progressive rainout of the Caribbean-sourced air masses as they move over the continent) and mean catchment altitude explain 84% of the oxygen-isotope variability of surface water in Belize and Guatemala (Lachniet and Patterson 2009). Surface water $\delta^{18}O$ values show an altitude effect of –1.9 to –2.4 ‰ km^{-1}, as well as a continental effect of 0.69 ‰ per 100 km once corrected for altitude (Lachniet and Patterson 2009). The area around Lamanai, however, does not have significant topographic variation. Thus, individuals moving within the region of northern lowland Belize would not be identified as non-local based solely on their $\delta^{18}O_p$ values. For example, oxygen-isotope compositions of individuals from sites like Chau Hiix and Altun Ha would not be identified as non-local to Lamanai. Detection of an outsider using oxygen isotopes would, in this instance, require them to have been from a significant distance away from Lamanai. Phosphate-oxygen isotope compositions have been measured previously for several sites in Mesoamerica (see Table 5.3-3). While an individual from the northern Belizean lowlands could not definitely be identified as non-local to Lamanai based on phosphate-oxygen isotope composition alone, other individuals (e.g., from West Mexico) certainly could be.

In the present study, only N10-12/6a's tooth oxygen-isotope composition can be easily identified as an outlier. However, this individual had one of the lowest Ag_3PO_4 yields for teeth and the highest $\delta^{18}O_p$ value in the study, and as mentioned in section 5.1.4, the moderate correlation between Ag_3PO_4 yields and $\delta^{18}O_p$ values could indicate modification of the original isotopic composition. However, it remains possible that this older, adult male did spend at least part of his childhood at a site with drinking water that was somewhat enriched in ^{18}O relative to Lamanai.

Overall, there is no individual whose bone or tooth phosphate-oxygen isotope composition definitively identifies them as a non-local to Lamanai. Although there are $\delta^{18}O_p$ values that fall outside of the baseline range, they do not do so as distinct outliers (except for N10-12/6a). In addition, most of the $\delta^{18}O_p$ values outside the Howie et al. (2010) baseline range are within methodological error from its boundaries. Still, this

study's samples have a range of $\delta^{18}O_p$ values > 3.4 ‰ (with N10-12/6a's value removed), which is larger than the ~ 2 ‰ intrapopulational variability expected in Mesoamerica (White et al. 1998; White et al. 2000; White, Spence et al. 2004; White, Storey et al. 2004). In addition, as discussed in section 5.3.4, several individuals likely experienced within-lifetime movement. It is also possible that some bone $\delta^{18}O_p$ values reflect partial tissue turnover for moves from foreign locations to Lamanai that occurred within the timeframe reflected by the bone. In short, while there is some mobility reflected in this Lamanai sample, most of the movement likely occurred within the climatically and physiographically similar lowland region surrounding Lamanai.

5.3.6   Comparison to Lamanai's Previous Mobility Findings

Although the temporal focus of Howie et al. (2010) is narrower (Terminal Classic and Early Postclassic periods only), the findings in this study agree relatively well with the general conclusions they arrived at about mobility at Lamanai. As in this study, Howie et al. (2010) found the oxygen-isotope compositions of their samples to be fairly continuous, which prevented them from identifying foreign locations. Their range of isotopic compositions encompassed ~ 5 ‰, which is larger than found in this study. However, once the single outlier from each study is removed, the range of oxygen isotopic compositions is quite similar (this study, 3.4 ‰; Howie et al. 2010, ~ 3.6 ‰). Howie et al. (2010) also found no difference in the oxygen-isotope composition of individuals between building groups, consistent with this study's finding that there is no difference between structure types. As with this study, some within-lifetime relocations were also identified by Howie et al. (2010), and they also suggested that Lamanai's inhabitants' "catchment area" is similar to Lamanai.

The $\delta^{18}O_p$ values in this study are consistent with those reported in White et al. 2009. However, while they found that the $\delta^{18}O_p$ values of enamel were consistently higher than bone by 1–2 ‰, this did not hold true in this study's expanded sample. White et al. (2009) focused on "The Loving Couple" (N11-5/7 A and B) and, using several lines of evidence, concluded that they were likely immigrants from West Mexico. As none of their isotopic data ($\delta^{13}C$, $\delta^{15}N$, or $\delta^{18}O_p$ values) were anomalous with individuals assumed to be Lamaneros, including $\delta^{18}O_p$ values from their M3s, it was suggested that they came

to Lamanai separately at an early age. However, their M1 $\delta^{18}O_p$ values analyzed in this study indicate that each spent the first few years of life at a site isotopically similar to Lamanai (Fig. 5.3-6), excluding a West Mexican origin (Table 5.3-3). The cultural markers indicating a West Mexican origin could instead indicate that they were at least second generation immigrants maintaining homeland traditions.

5.3.7 Change between the Postclassic and the Historic Period

As presented in Chapter 3, the Postclassic was a time of prosperity and trade at Lamanai, and the Historic period saw at once great changes and in many ways a continuance of daily life. The $\delta^{18}O_p$ data point to two possible differences between the time periods: (1) a downward shift in mean $\delta^{18}O_p$ values, and (2) potential difference in mobility patterns between the sexes.

5.3.7.1 Temporal Shift in $\delta^{18}O_p$ Values: Changing Climate or Mobility Patterns?

Section 5.3.1 demonstrated a small downward shift in the mean $\delta^{18}O_p$ values of both bone and tooth enamel by 0.6 ‰ from the Postclassic to the Historic period (Figs. 5.3-1a, b). There are two possible explanations: climate fluctuation or differential mobility patterns. The two explanations are not mutually exclusive and with the current data, no clear choice between them is possible.

Let us first consider climate fluctuations. The sampled individuals span ~ 700 years, which is sufficient time for significant climate change or several cycles of climate fluctuations to occur. Postclassic individuals represent the largest portion of the time span, extending over 500 years (950/1000 AD to ~ 1500 AD). Historic individuals represent a much narrower time span, as the church from which they were excavated was only in use for about 100 years after it was built in ~ 1544 (section 3.2.5).

Several studies of climate change in the Maya area demonstrate variability in climate during the last 1500 years (e.g., Aragón-Moreno et al. 2012, Medina-Elizalde et al. 2010; Curtis et al 1996, Hodell et al. 2005; Webster 2007). Curtis et al. (1996) suggested repeated multi-decadal wet/dry cycles that overlay longer term patterns of abundant

rainfall and drought, while Medina-Elizalde et al. (2010) reported significant variability at inter-annual, multi-decadal, and centennial levels in the region. Many studies have found evidence for several periods of drought intermixed with wetter conditions in the Yucatan Peninsula spanning the Terminal Classic into the Early Postclassic period (Curtis et al. 1996; Hodell et al. 2005; Hodell et al. 2007; Medina-Elizalde et al. 2010; Medina-Elizalde and Rohling 2012). A stalagmite record in the Vaca Plateau, Belize also records a series of droughts from 700 to 1135 AD (Webster et al. 2007). After some of the driest conditions in the last 3800 years (~ 1000 AD), the trend during the Postclassic and beyond was towards wetter conditions, except for a dry episode around the 1400s (Aragón-Moreno et al. 2012; Curtis et al. 1996; Hodell et al. 2007; Webster 2007). Unfortunately, S. Metcalfe al.'s (2009) study of cores from the New River Lagoon does not have sufficient resolution to identify short-lived shifts in climate.

The phosphate-oxygen isotope data fit the evidence for climate fluctuations in two major ways. First, the downward shift in $\delta^{18}O_p$ values, as observed from the Postclassic into the Historic period, would be expected if the climate shifted from drier to wetter. Second, increased variability in the Postclassic $\delta^{18}O_p$ values is also consistent with climatic fluctuations described above. This variability would be reflected in drinking water $\delta^{18}O$ values, which would in turn be transferred to the $\delta^{18}O_p$ values of individuals from this time period. Periods of drought would result in higher $\delta^{18}O$ values, with the opposite occurring during periods of abundant rain. The Postclassic individuals have larger ranges of $\delta^{18}O_p$ values and a coefficient of variation more than 1.5 times larger than the Historic period. With such a comparatively narrow time span represented by the Historic individuals, it not surprising that this period recorded a smaller range and less variation in its bone $\delta^{18}O_p$.

The larger Postclassic variation in $\delta^{18}O_p$ values could also be explained by greater mobility. The large continuous range of variation in $\delta^{18}O_p$ values in the Postclassic suggests the potential for greater within-lifetime mobility of individuals than in the Historic period, particularly within the relatively "local" area. During the Postclassic, as discussed in Chapter 3, Lamanai was well-connected to other sites through the sharing of trade goods and ideas. These connections necessitated the movements of people. The

addition of a few individuals from areas with drinking water δ^{18}O values only slightly more positive than Lamanai's could be enough to increase the average δ^{18}O$_p$ value of the Postclassic group. In addition, if some individuals from Lamanai were participating in back and forth travel (e.g., for trade or to foster alliances) as opposed to relocation, this practice could also increase the range of variability seen in the bone δ^{18}O$_p$ values.

5.3.7.2   Sex Differences in Mobility Over Time

During the Postclassic period, females have much larger |Δ^{18}O$_{p\ enamel\text{-}bone}$| than males. This observation holds true when the sexed Postclassic individuals from Howie et al. (2010) and White et al. (2009) are also included[47]. The larger |Δ^{18}O$_{p\ enamel\text{-}bone}$| of Postclassic females suggests a greater difference than observed for males between the water sources ingested as children versus adults. This could indicate greater within-lifetime mobility for females than males, or that female within-lifetime movements involve relocations between more climatically and/or physiographically different areas. The mid-size to large (1.0 to 4.3 ‰) |Δ^{18}O$_{p\ enamel\text{-}bone}$| in females[48], which was not observed in males, may reflect a difference in mobility between the sexes, and possibly reflects patrilocal marriage patterns during the Postclassic.

In the Historic, males show a larger range of bone δ^{18}O$_p$ values than females, suggesting that not all Historic males buried at Lamanai spent the last years of their lives living in the same location as each other. In contrast, Historic females have a much larger range of enamel δ^{18}O$_p$ values than males. This range of > 3 ‰ suggests that they were not all born and/or spent their childhood at the same location, and, along with the |Δ^{18}O$_{p\ enamel\text{-}bone}$| patterns discussed in section 5.3.4, may suggest a possible partial continuation of the Postclassic female mobility pattern.

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[47] In the combined dataset, males' mean |Δ^{18}O$_{p\ enamel\text{-}bone}$| of 0.8 ± 0.5 ‰ (n = 14) is much smaller than the females' (1.9 ± 1.0 ‰, n = 13), and the groups' |Δ^{18}O$_{p\ enamel\text{-}bone}$| are significantly different [U = 159.5, z = 3.325, p = 0.001].

[48] With a |Δ^{18}O$_{p\ enamel\text{-}bone}$| of 0.4 ‰, N10-4/2B from Howie et al. 2010 was the only female with an absolute difference < 1.0 ‰.

5.4 Collagen Carbon- and Nitrogen-Isotope Data

5.4.1   Diet Data Collected During this Study

Carbon- and nitrogen-isotope data for bone collagen were also collected from individuals included in this study (n = 33) who had not been analyzed in the previous isotopic diet studies of White and Schwarcz (1989) or Howie et al. (2010). For the samples analyzed in this study, the Postclassic individuals have an average δ^{13}C value of –8.5 ± 0.5 ‰ (n = 12), ranging from –9.4 to –7.7 ‰. Historic period samples have slightly lower δ^{13}C values with an average of –9.0 ± 0.5 ‰ (n = 21), and a range of –10.0 to –8.1 ‰. The difference in mean δ^{13}C values between the two time periods is statistically significant [t(31) = 2.278, p = 0.030]. There are no identifiable outliers in either time period (Fig. 5.4-1a).
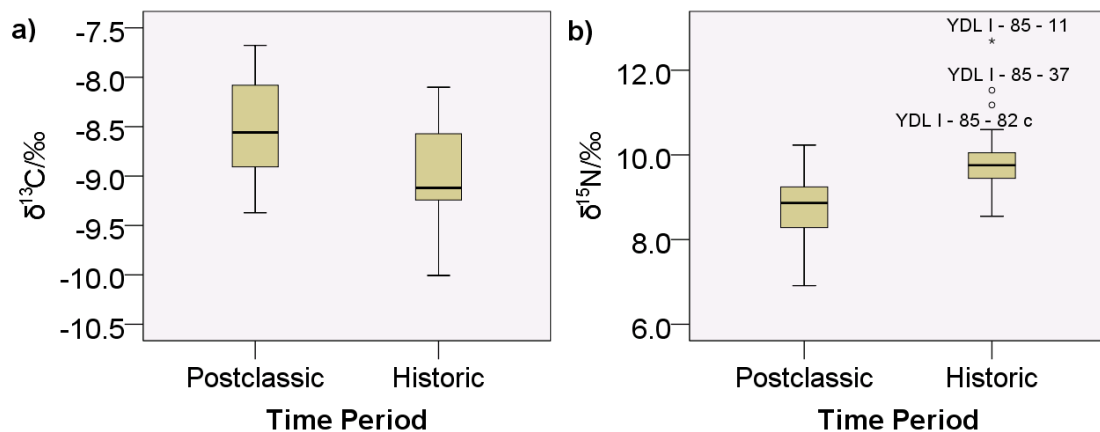
Figure 5.4-1 Boxplots of Lamanai collagen isotopic compositions subdivided by time period showing a) δ^{13}C and b) δ^{15}N

The δ^{13}C values of individuals from both of these time periods indicate that C_4 sources (such as maize or maize-fed animals) and/or input from marine, reef, or estuarine sources composed a significant portion of the protein component of their diet.   The slight decrease in δ^{13}C values from the Postclassic to the Historic period could indicate a decrease in the reliance on these sources, and increased consumption of C_3 plants, C_3-fed terrestrial animals, or freshwater fish.

Postclassic individuals have an average δ^{15}N value of +8.7 ± 0.9 ‰ (n = 12), ranging from +6.9 to +10.2 ‰, while Historic period samples have a statistically significant [t(31) = −3.487, p = 0.001], 1.2 ‰ higher average of +9.9 ± 1.0 ‰ (n = 21), ranging from +8.6 to +12.7 ‰. The overall range of 5.8 ‰ in δ^{15}N values among the samples, and ranges of 3.3 ‰ in the Postclassic and 4.1 ‰ in the Historic, suggest "trophic level" differences among the individuals at Lamanai even within a single time period. The mean δ^{15}N values for both the Postclassic and the Historic periods fall into the mid to high end of the Maya area omnivore (i.e., dogs) range, which is ~ +7 to +10 ‰ (van der Merwe et al. 2000; White, Pohl et al. 2001). This suggests consumption of significant amount of animal and/or fish proteins, with amount increasing in the Historic period. Even when a possible breastfeeding effect has been removed (see below) by considering only Postclassic and Historic period individuals over 10 years of age, a statistically significant difference remains between the two time periods [t(26) = 2.924, p = 0.007].

In the Historic period there are three individuals whose δ^{15}N values can be considered outliers: YDL-85-11, YDL-85-37, and YDL-85-82c (Fig. 5.4-1b). These samples are all children, and likely are exhibiting the effects of ^{15}N enrichment arising from breastfeeding (Herring et al. 1998; Schurr 1998; Dupras et al. 2001; Richards et al. 2002; Schurr and Powell 2005; Fuller et al. 2006). YDL-85-11 and YDL-85-37, which have the highest values, are both under 2 years of age, meaning that they were likely breastfeeding as the common weaning age at Lamanai was between 2 and 6 years of age (White et al. 1994; White et al. 1997). YDL-85-82c was tentatively aged between 5 and 8 years old. It is possible that the bone was in the process of turning over, and while it had started to fall in line with the "standard" Lamanero diet, the higher δ^{15}N values of the child's breastfeeding days were still reflected. The child may also have suffered from an extended illness, which can also cause higher δ^{15}N values as the body catabolizes its own tissues (Katzenberg and Lovell 1999).

In sum, there is a slight decrease in δ^{13}C values and an increase in δ^{15}N values from the Postclassic to Historic periods. Figure 5.4-2 illustrates that the δ^{15}N values increase (implying consumption at a slightly higher trophic level) at the same point as δ^{13}C values decrease, and this relationship becomes even clearer when samples possibly affected by a

breastfeeding effect are removed (Pearson's r = –0.495, df = 27). Thus, it is unlikely that the change in δ^{13}C values is caused by increased C_3 plant consumption. It seems that individuals consuming foods in the C_4 range (e.g., maize) were generally eating less animal protein from the C_3 range of values (i.e., C_3-eating terrestrial animals or freshwater fish). Overall, the Historic individuals plot slightly farther from C_4 foods and slightly higher up the food chain, suggesting that they were eating slightly more C_3-eating terrestrial animals or freshwater fish than Postclassic individuals.
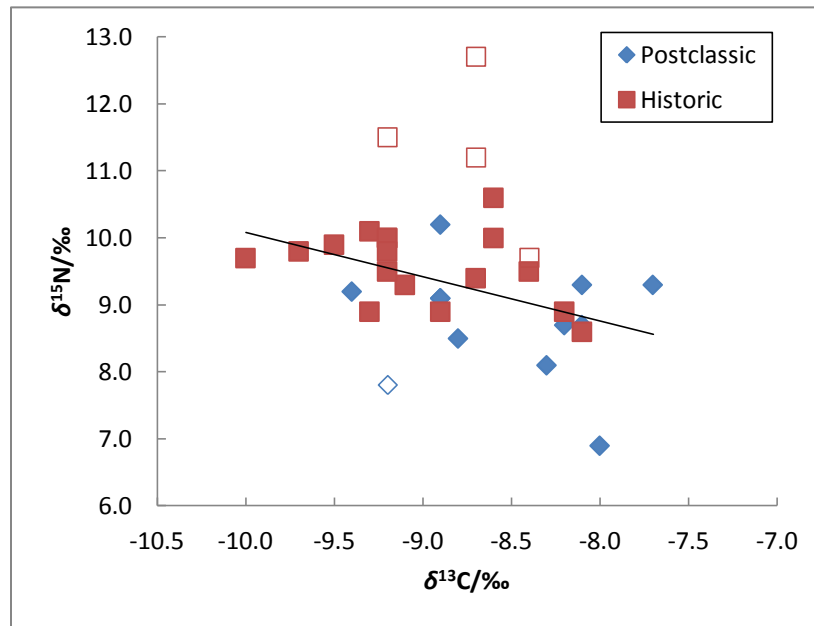
Figure 5.4-2 Distribution of Lamanai collagen δ^{13}C and δ^{15}N values from this study. Unfilled data points represent Juveniles (under 10 years of age) excluded from the best-fit line to avoid any impact from breastfeeding.

5.4.1.1 Comparison of Diet Data by Sex

To investigate whether there were any sex differences in the diet data, only individuals with definite sex determinations were used (n = 25). There was no difference in mean δ^{13}C values between males (–8.8 ± 0.6 ‰, n = 15) and females (–8.8 ± 0.7 ‰, n = 10) nor any difference in mean δ^{15}N values between males (+9.2 ± 0.6 ‰, n = 15) and females (+9.2 ± 0.9 ‰, n = 10). When the individuals are subdivided by time period, the differences between the sexes are not statistically significant for either δ^{13}C or δ^{15}N

(Table 5.4-1). The only notable difference is that Postclassic females appear to have more variability in δ^{15}N than their male counterparts, possibly suggesting more variability in the consumption of proteins. That said, N10-4/33, with her low δ^{15}N value of +6.9 ‰, contributes significantly to the appearance of higher variability in nitrogen-isotope compositions of Postclassic females. Her nitrogen-isotope composition suggests that she ate a significantly smaller proportion of terrestrial animals, freshwater fish, or marine fish than the rest of the Postclassic population, and Lamaneros overall. Her δ^{13}C value of −8.0 ‰ is at the high end of the Postclassic range, and suggests a larger contribution of C_4 plants, C_4-consuming animals, and/or marine/reef resources to her diet than other Postclassic Lamanai individuals. Given that her protein was derived from a relatively low trophic level, C_4 plants (i.e., maize) or possibly marine invertebrates are the most likely sources.

Table 5.4-1 Male and Female δ^{13}C and δ^{15}N Values Subdivided by Time Period

Time Period	δ^{13}C or δ^{15}N	Sex	n	Mean /‰	Std. Deviation	t	df	p
		Male	5	−8.6	0.6			
	δ^{13}C	Female	4	−8.3	0.4	−0.895	7	0.401
		Male	5	8.8	0.5			
Postclassic	δ^{15}N	Female	4	8.5	1.1	0.604	7	0.565
		Male	10	−8.9	0.5			
	δ^{13}C	Female	6	−9.2	0.5	0.896	14	0.385
		Male	10	9.4	0.5			
Historic	δ^{15}N	Female	6	9.7	0.3	−1.539	14	0.146

5.4.1.2   Comparison of Diet Data by Age

As a result of the age distribution of individuals between and within time periods, comparisons between age groups not subdivided by time are not appropriate because all age groups do not have significant representation in all time periods. In addition, given the small sample size of the Postclassic collagen sample, no meaningful comparisons were possible between any age groups (Table 5.4-2). In the Historic period, the mean δ^{13}C values of Adults and Juveniles are similar; however, the mean δ^{15}N value of the Juveniles is 1.7 ‰ higher than the mean δ^{15}N values of the Adult group. This difference

and the variability of Juvenile δ^{15}N values are likely due to variable expression of the breastfeeding effect in the majority of these children, as discussed earlier.

Table 5.4-2 Postclassic and Historic Bone Collagen δ^{13}C and δ^{15}N Values Subdivided by Age from this Study as well as from the Combined Dataset

Data-set	Time Period	Age Group	n	δ^{13}C/‰			δ^{15}N/‰		
				Mean	Min.	Max.	Mean	Min.	Max.
This Study	Post-classic	Juveniles	1	–9.2	—	—	+7.8	—	—
		Young Adults	2	–8.7 ± 0.9	–9.4	–8.1	+8.9 ± 0.4	8.7	9.2
		Adults	9	–8.4 ± 0.5	–8.9	–7.7	+8.8 ± 0.9	6.9	10.2
	Historic	Juveniles	4	–8.8 ± 0.3	–9.2	–8.4	+11.3 ±1.2	9.7	12.7
		Adults	17	–9.0 ± 0.5	–10.0	–8.1	+9.6 ± 0.5	8.6	10.6
Combined	Post–classic	Juveniles	6	–8.9 ± 0.7	–9.9	–8.1	+9.8 ± 1.6	7.8	11.5
		Young Adults	5	–9.2 ± 0.7	–12.0	–7.5	+8.7 ± 0.3	8.5	9.2
		Adults	38	–9.1 ± 0.8	–9.9	–8.1	+9.1 ± 0.8	6.9	10.7
	Historic	Juveniles	4	–8.8 ± 0.3	–9.2	–8.4	+11.3 ± 1.2	9.7	12.7
		Adults	26	–9.2 ± 0.6	–10.2	–8.1	+9.6 ± 0.6	8.5	10.8

5.4.2   Discussion of Lamanai's Diet Data

The carbon- and nitrogen-isotope data gathered in this study adds to and bolsters previous work done on diet at Lamanai (Fig. 5.4-3). Here, isotopic results for bone collagen from White and Schwarcz (1989) (n = 31) and Howie et al. (2010) (n = 16) are combined with the data gathered in this study. The mean δ^{13}C value is slightly higher in this study's dataset in both the Postclassic and Historic periods, by ~ 0.6 ‰ [t(47) = 2.520, p = 0.015] and 0.7 ‰ [t(28) = 3.581, p = 0.001] respectively, than in the combined previous studies. This small difference does not affect overall interpretations of diet. For nitrogen-isotope compositions, there is no statistically significant difference between the studies for either time period [Postclassic t(47) = –1.868, p = 0.068; Historic t(28) = 0.335, p = 0.656].

Previous dietary studies subdivided Lamanai's history into Early and Late periods. Both of the time periods investigated in this thesis (Postclassic and Historic) make up the Late period, with previous periods (Preclassic to Terminal Classic) being grouped together in the "Early" category. There is a significant increase in δ^{13}C values in the Late period relative to earlier times at Lamanai (Coyston et al. 1999:232). Coyston et al. (1999) suggest that this shift was related to protein consumption for a few reasons. First, the
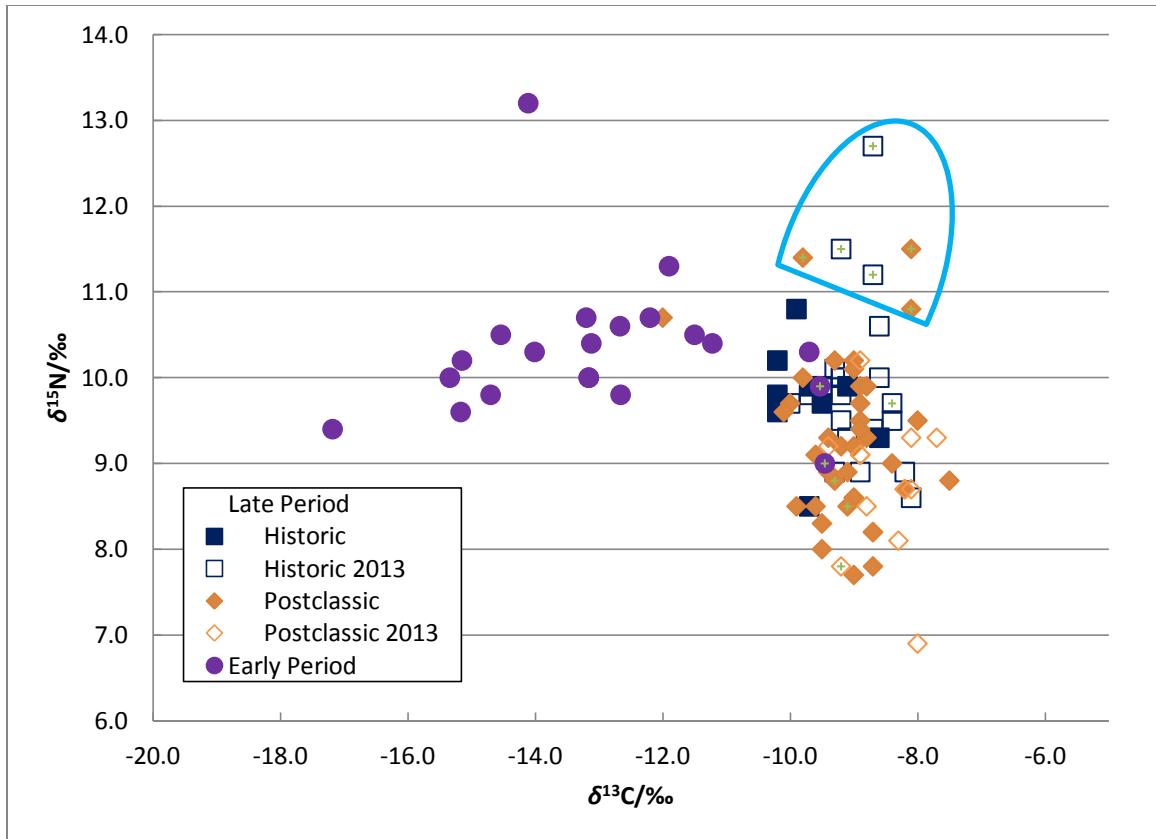
Figure 5.4-3 All bone collagen carbon- and nitrogen-isotopic data from Lamanai. Data from this study are represented by open data points, while the other data are from White and Schwarcz (1989) and Howie et al. (2010). Those individual with elevated δ^{15}N values circled in light blue are Juveniles (as indicated by the overlain green cross) possibly demonstrating the influence of breastfeeding.

shift is more apparent in collagen, which represents dietary protein, than in carbonate, which more closely reflects whole diet. Second, the average nitrogen-isotope composition of the Early period is 1 ‰ higher than the Late Period and negatively correlated with collagen δ^{13}C values, suggesting a link between the nitrogen source (protein) and the change in carbon. While consumption of maize could have increased (replacing C_3 terrestrial animals), Coyston et al. (1999) suggest that reef fish and shellfish may have been substituted for some terrestrial animals or that Late period Lamaneros ate both more maize and more marine resources. Postclassic middens contain abundant fish

remains, with an increased abundance recovered from Historic period contexts (Emery 1990, 1999).

These patterns are supported by the data for more recent studies of Lamanai (i.e., Howie et al. 2010 and this study). The Early period mean δ^{13}C value of -13.0 ± 2.0 ‰ (n = 21) is significantly lower than the Late period's mean δ^{13}C value of -9.1 ± 0.7 ‰ (n = 80) [t(21.242) = -8.830, p < 0.0005]. As with Coyston et al.'s (1999) data, the average δ^{15}N value of the Early period ($+10.3 \pm 0.8$ ‰, n = 21) is significantly higher (by ~ 1 ‰) than in the Late period ($+9.4 \pm 1.0$ ‰, n = 80) [t(99) = 3.931, p < 0.0005].

5.4.2.1   Comparison of Diet Data by Time Periods

Previously reported isotopic data for Lamanai show a decrease in average δ^{13}C and an increase in δ^{15}N values from the Postclassic to the Historic period, but these differences were not statistically significant (Coyston et al. 1999; White and Schwarcz 1989). For the combined dataset, the Postclassic period mean δ^{13}C value of -9.0 ± 0.7 ‰ (n = 49) is not statistically different from the Historic period δ^{13}C mean of -9.2 ± 0.6 ‰ (n = 30) [t(77) = 1.251, p = 0.215]. In the grouped data, there are a few individuals identified as carbon-isotope outliers (Fig. 5.4-4a). In particular, N10-2/7's low δ^{13}C value is an extreme outlier for Postclassic Lamanai, and with a higher than average δ^{15}N value his
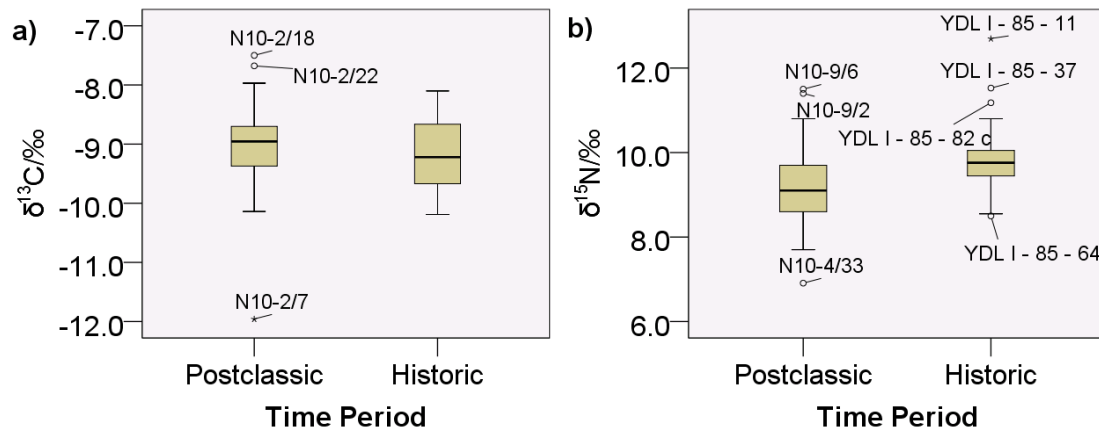
Figure 5.4-4 Boxplots of Lamanai collagen from the combined dataset subdivided by time period showing a) δ^{13}C and b) δ^{15}N

diet appears closer to an "Early" period diet. The Postclassic period mean δ^{15}N value of +9.2 ± 0.9 ‰ (n = 49) for the combined dataset is statistically lower than the Historic δ^{15}N mean of +9.9 ± 0.9 ‰ (n = 30) [t(77) = −3.312, p = 0.001]. Most outliers are juveniles with δ^{15}N values likely influenced by breastfeeding. Overall, the combined dataset does not indicate a major dietary shift between the Postclassic and Historic periods.

5.4.2.2 Comparison of Diet Data by Sex

Coyston et al. (1999) found that dietary isotopic data could not be used to distinguish status differences in sex when the Postclassic and Historic individuals were combined into a singular "Late" period, which was also the case for the data from this study. When all available securely sexed bone collagen data from Lamanai are combined, the results are similar. The mean δ^{13}C values of males (−9.0 ± 0.8 ‰, n = 32) and females (−9.1 ± 0.6 ‰, n = 26) are almost identical [t(56) = 0.418, p = 0.678], as are the interquartile ranges (Fig. 5.4-4a). There is also no difference [t(56) = 0.153, p = 0.870] in the mean δ^{15}N values of males (+9.3 ± 0.7 ‰, n = 32) and females (+9.3 ± 0.8 ‰, n = 26) (Fig. 5.4-4b). Overall, there were no significant differences in the diets of males and females at Lamanai during the Late part of its history.

Investigating the possibility of sex differences in each of the time periods that composed this "Late" period ensures that potential differences are not masked. No significant difference in the mean δ^{13}C or δ^{15}N values of males and females in the Postclassic was found in the data from the present study, but, based on collagen isotopic data from White and Schwarcz (1989), White (2005) suggested that males (δ^{13}C: $\bar{x}$ = −9.5 ± 1.0 ‰, n = 11) consumed slightly less maize than females (δ^{13}C: $\bar{x}$ = −9.1 ± 0.5 ‰, n = 7), and that males (δ^{15}N: $\bar{x}$ = +9.7 ± 0.7 ‰, n = 11) accessed protein from a slightly higher trophic level than females (δ^{15}N: $\bar{x}$ = +9.1 ± 0.5 ‰, n = 7). This study's means show similar patterning (Table 5.4-1), but with smaller (and not statistically significant) differences. The difference between these studies is likely due to small sample sizes.

When all available, securely-sexed bone collagen data from Lamanai are used, the picture begins to clarify. During the Postclassic period, the slightly lower mean δ^{13}C value of

males (-9.0 ± 1.0 ‰, n = 19) is statistically the same [t(32) = -0.742, p = 0.464] as the mean δ^{13}C value of females (-8.8 ± 0.5 ‰, n = 15). There is a slightly higher mean δ^{15}N value in the combined Postclassic males ($+9.2 \pm 0.8$ ‰, n = 19) than in the Postclassic females ($+8.9 \pm 0.8$ ‰, n = 15), but the difference is not statistically significant [t(32) = 1.229, p = 0.228]. While males may have consumed slightly less maize and obtained their protein at a slightly higher trophic level than females, this difference, if real, is not a large one.

For the Historic period, White (2005) reported no sex differences in maize consumption or protein source, as was the case in the present study, although for both there is a small difference between the means (Table 5.4-1). In the combined dataset, the Historic period mean δ^{13}C value of males (-9.0 ± 0.6 ‰, n = 13) is slightly higher than the female mean (-9.5 ± 0.6 ‰, n = 11), but this difference is not statistically significant [t(22) = 2.048, p = 0.053]. A lack of significance [t(22) = -1.904, p = 0.070] is also found for the difference between the mean δ^{15}N value of Historic period males ($+9.5 \pm 0.5$ ‰, n = 13) and females ($+9.8 \pm 0.4$ ‰, n = 11). In summary, while the possibility of sex differences in diet during the Postclassic was noted by White (2005), the larger combined dataset does not reveal significant differences between the sexes in either the Postclassic or Historic period, nor in Lamanai's "Late" period as a whole.

5.4.2.3   Comparison of Diet Data by Age

In both the Postclassic and Historic period, all sampled age groups' mean δ^{13}C values were similar (Table 5.4-2). In contrast, in both time periods the Juvenile average δ^{15}N values are higher, and the Juvenile groups have a lot of variation. This may indicate individuals at different stages of breastfeeding/weaning. An analysis of ages (not presented here) found that within this sample, breastfeeding and weaning, as indicated by δ^{15}N values, does not easily break down by age, suggesting non-uniform practices. This heterogeneous breastfeeding/weaning behaviour likely reflects variability in social practices within the population, as this process can be a very individual experience (Marquis et al. 1998).

5.4.2.4   Comparison of Lamanai Diet to Other Sites

Since the initial Lamanai diet data were published (White and Schwarcz 1989), there have been several comparisons with other sites in the Maya area (*inter alia* Coyston et al. 1999; Gerry and Krueger 1997; J. Metcalfe et al. 2009; Somerville et al. 2013; Williams et al. 2009; White 1997, etc.). Overall, inhabitants of Lamanai depended less on maize and more on marine foods than those from other sites in the region (Coyston et al. 1999; Gerry and Krueger 1997; Howie et al. 2010). Coastal Belizean sites (e.g., Marco Gonzalez), however, consumed more marine resources than Lamanai (Williams 2000; Williams et al. 2009). In addition, at nearby Chau Hiix, the individuals ate relatively less maize (or more C_3 plants) and more C_4-fed terrestrial animals, marine, or reef proteins, even while paralleling Lamanai's changes in diet over time (J. Metcalfe et al. 2009).

5.4.3   Diet Continuity and Change between the Postclassic and Historic Period

As is true of so many aspects of Lamanai's transitions between time periods, there are elements of both continuity and change in Lamanai's diet. As discussed throughout section 5.4, the overall diet at Lamanai between the Postclassic and Historic period remained relatively stable. This is true particularly compared to the dietary shift between Lamanai's Early and Late periods. As described by Coyston et al. (1999), Postclassic and Historic Lamaneros ate significant amounts of maize, and likely ate more marine animals than during earlier time periods.

The slight decrease in $\delta^{13}C$ values measured in this study from the Postclassic to the Historic period could indicate a decrease in reliance on C_4 sources and increased consumption of C_3 resources. However, the difference between the two periods is very small, and not statistically significant in the combined dataset. There is a small increase in $\delta^{15}N$ values between the periods that may indicate consumption of a slightly greater proportion of terrestrial animals or fish. Emery's (1990, 1999) findings of even greater quantities of fish remains in the Historic than the Postclassic lends support to this explanation. There were no statistically significant differences in diet between the sexes

for either time period, and in both time periods Juveniles had more positive δ^{15}N values, reflecting breast-milk consumption.

5.5   Getting to Know the VPLFs

A goal of this study was to investigate the Postclassic individuals buried in the VPLF position (Ventrally Placed, Legs Flexed; section 3.4.1) in order to begin to understand who the individuals buried in this distinct position were, and the reason for the emergence of this mortuary behaviour. Specifically, do these individuals represent non-locals/immigrants or is the appearance of this burial practice tied into other changes occurring at Lamanai?

5.5.1   Description

While there is significant variability in the burial position and grave accompaniments, the key is that all individuals included in this category are described as ventrally placed (lying on their stomachs) with their legs bent back so that their feet are on their pelvis. It has been suggested that the legs were bound before burial, to keep the feet in place on the pelvis (Graham et al. 2013). There is significant variation in the positioning of the hands and arms (e.g., by their sides, flexed, across the chest, etc.); however there is no readily apparent association between these types of variability and time period, structure, age, or sex. The cardinal orientation of the burials also does not seem to be explained by these factors, and there is no standard orientation.

These burials are dated using ceramics and stratigraphy. While the majority of the VPLFs date to the Early Postclassic, this burial position at Lamanai persisted through the Early and Middle Postclassic Period and likely into the Late Postclassic as well. Although the VPLF burial position is unusual, it was not uncommon at Lamanai as more than one-third of all individuals for whom burial position is available are categorized as such. It crosscuts sex and age groups, with both sexes as well as all age groups (from children to old adults) found interred in this fashion.

The burials were found in a number of structures on the site including the Ottawa Group, N10-2, and N10-4. Although the Ottawa Group and N10-4 were both residences of the

site's elite, the Ottawa group has been interpreted as the home of the site's most prominent elite group. Therefore, the practice is also not tied to degree of eliteness. VPLF burials have also been documented elsewhere, including at the nearby site of Chau Hiix (Wrobel 2007) and in the coastal region of Belize at sites like Marco Gonzalez and San Pedro (Graham 2004:235; Graham et al. 2013; Wrobel and Graham *in press*)[49].

5.5.2   Exploring the Origins of the VPLFs and Other Burials in the Postclassic Period

As the VPLF position is so distinct and was a relatively new development at Lamanai, it makes sense to explore the possibility that individuals buried in this way were not from Lamanai. Although the mobility and geographic origins of the VPLFs at Lamanai have not explicitly been studied before, Wrobel and Graham (*in press*) used dental morphology to explore the possibility of a non-local origin for Lamanai's Early Postclassic individuals associated with the Buk ceramic phase – many of whom are VPLFs. They suggest that these "Buk-phase" individuals are genetically distinct from Lamanai's Late to Terminal Classic population because of recent non-local origins or non-local elites marrying into local families. The study was unable to resolve the issue as a result of a less than ideal sample and conflicting results (Wrobel and Graham *in press*).

In both White et al. (2009) and Howie et al. (2010) isotopic data relevant to mobility for several individuals buried in the VPLF position were produced. This information was combined with the data collected in this study to strengthen statistical validity by increasing sample size (the overall results of the combined dataset analyses are the same as when only this study's data are considered). The combined $\delta^{18}O_p$ data[50] for bone and tooth enamel of Postclassic individuals with known burial position are shown in Figure 5.5-1. There is no difference in the mean bone $\delta^{18}O_p$ values of individuals buried in the

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[49] Additional potential VPLF burials have been identified through illustrations of Terminal Classic burials in Willey et al.'s (1965) site report from Barton Ramie in the Belize River Valley (Wrobel and Graham *in press*).

[50] This combined dataset represents the data collected in this study and White et al. 2009 (averaged in cases of overlap), as well as the Howie et al. (2010) mobility data (after conversion from $\delta^{18}O_{sc}$ to $\delta^{18}O_p$ as per section 5.3.5).
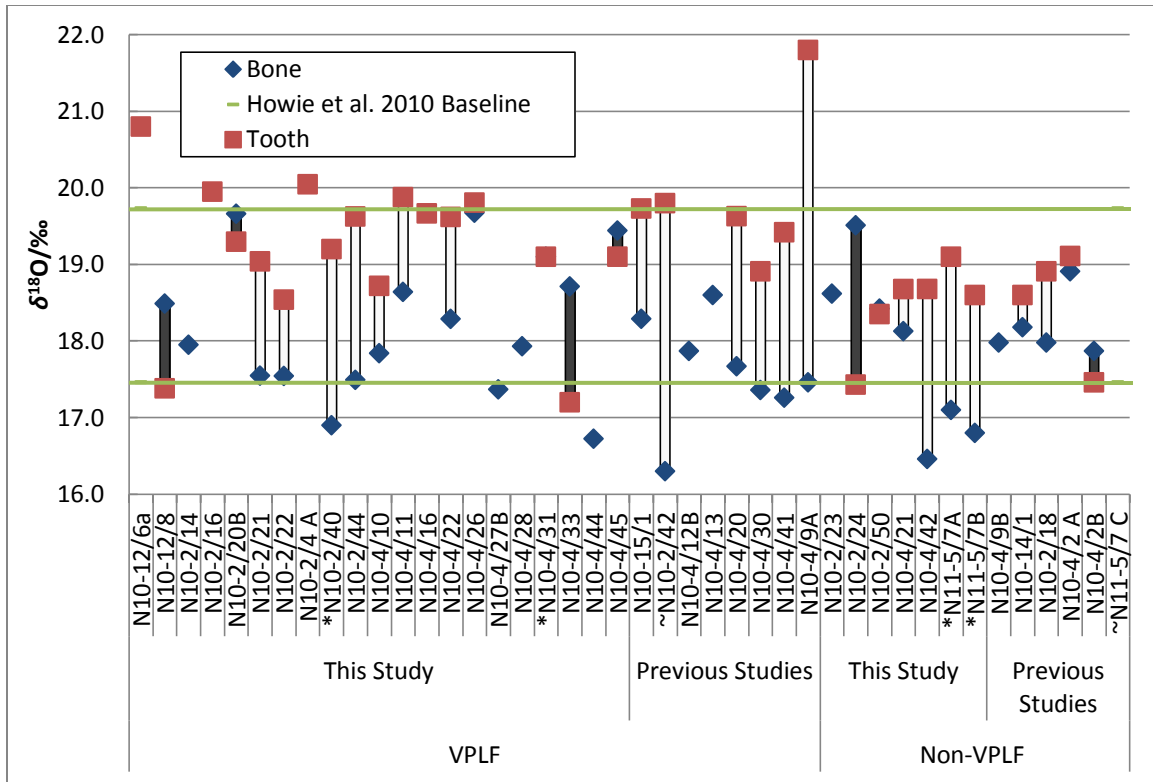
Figure 5.5-1 Enamel and bone $\delta^{18}O_p$ values of Postclassic individuals with known burial position data from this study, White et al. (2009), and Howie et al. (2010). Individuals with $\delta^{18}O_p$ values averaged with White et al. (2009) are marked with an asterisk (*). All "Previous Studies" individuals are from Howie et al. (2010) except for the White et al. (2009) data indicated with a tilde (~).

VPLF position (+18.0 ± 0.9 ‰, n = 25) versus other positions during the Postclassic (+17.9 ± 0.9, n = 13) [t(36) = 0.399, p = 0.692]. This supports the idea that many of the individuals in both groups spent the years leading up to their death in a similar area, likely Lamanai, as both groups' $\delta^{18}O_p$ value averages fall within the Howie et al. (2010) Lamanai baseline (+17.5 to +19.7 ‰).

Similar to the findings of this study's dataset alone, the combined dataset for VPLF-buried individuals has a mean tooth enamel $\delta^{18}O_p$ value of +19.4 ± 1.0 ‰ (n = 23) versus +18.5 ± 0.6 ‰ (n = 10) for individuals buried in other positions; this difference is statistically significant [t(33) = 2.774, p = 0.009]. The 4.6 ‰ range in tooth enamel $\delta^{18}O_p$ values for VPLF individuals encompasses the entire variation measured for the rest of

Postclassic individuals. This suggests that: (1) some VPLF individuals were born/spent some of their early years in a similar climate region as the non-VPLF individuals; and (2) not all of the VPLF individuals were born/spent the first few years of their lives in the same location as each other and non-VPLF individuals. That said, the enamel oxygen-isotope averages for both groups do fall within the Lamanai baseline, so it is likely that many individuals from both groups spent some of their childhood at Lamanai (or a nearby site with a similar drinking water composition).

Figure 5.5-1 shows that the majority of VPLF individuals lived their life, or at least part of their life, in a region with drinking water isotopic compositions like Lamanai. However, not all of them were local. N10-4/9A, for example, was clearly born elsewhere, but as noted by Howie et al. (2010), she moved to and lived in an area like Lamanai for at least 10–15 years before her death. N10-12/6a also appears to have spent his early years away from Lamanai[51].

5.5.3   Diet

Dietary data for the VPLF individuals were explored to determine if they were dietarily distinct, which could indicate non-locals or suggest maintenance of foreign dietary traditions. There is no significant difference [$t(35) = 1.361$, $p = 0.182$] between the mean $\delta^{13}C$ value of individuals buried in the VPLF position (-8.8 ± 0.6 ‰, n = 24) and other positions (-9.2 ± 1.1 ‰, n = 13), based on data for Postclassic individuals for whom burial position and collagen isotopic data are available (this study, n = 11; White and Schwarcz 1989, n = 13; Howie et al. 2010, n = 13) (Fig. 5.5-2a). There is also no significant difference [$t(35) = -1.848$, $p = 0.073$] between the mean $\delta^{15}N$ value of individuals buried in the VPLF position ($+8.9 \pm 0.9$ ‰, n = 24) and other positions ($+9.4 \pm 0.7$ ‰, n = 13). However, there does appear to be a wider spread of $\delta^{15}N$ values in the VPLF individuals (Fig. 5.5-2b), which may suggest greater variety in the trophic level of their protein sources.

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[51] As discussed in section 5.3.5, the $\delta^{18}O_p$ value of the sample remains questionable.
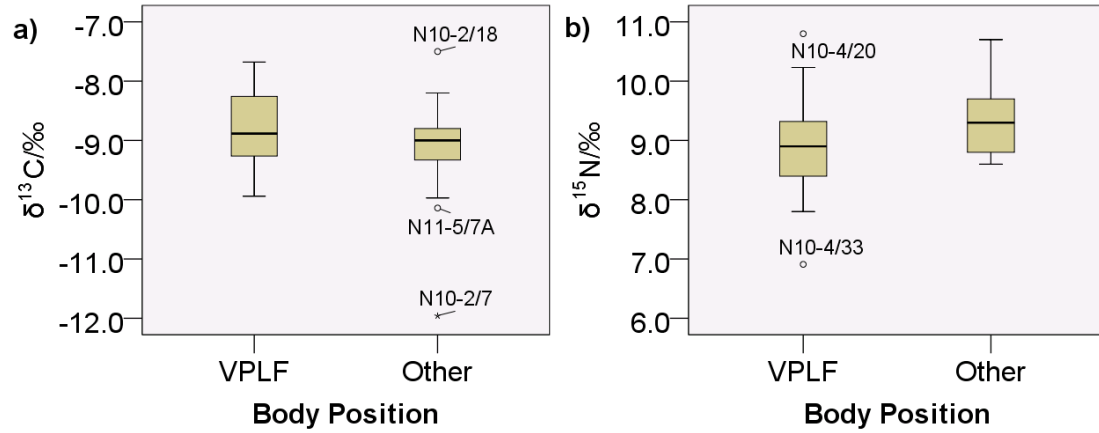
Figure 5.5-2 Boxplots of Lamanai collagen isotopic compositions from the combined dataset subdivided by burial position showing a) δ^{13}C and b) δ^{15}N
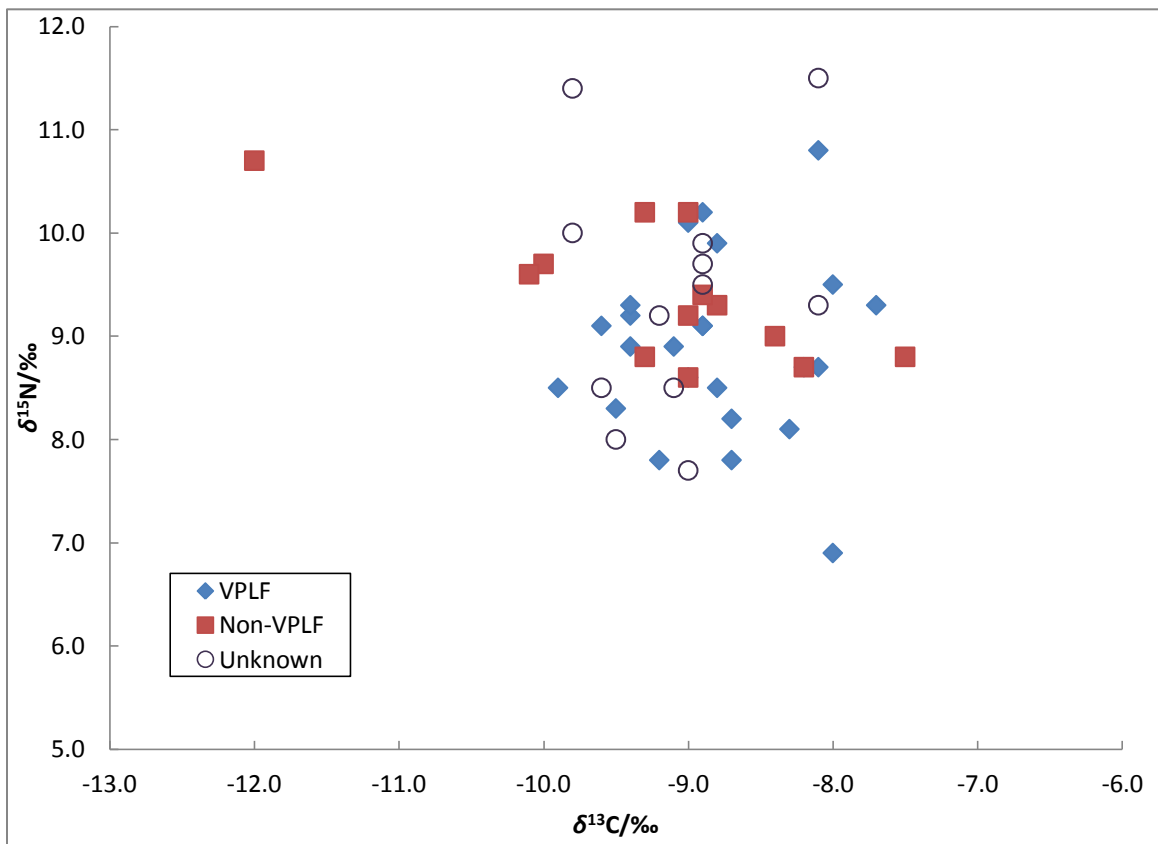
Figure 5.5-3 Bone collagen δ^{15}N versus δ^{13}C for Postclassic individuals subdivided by burial position. Data presented are from this study, White and Schwarcz (1989), and Howie et al. (2010).

The carbon- and nitrogen-isotope compositions of the VPLF group cluster together for the most part (Fig. 5.5-3) with only two "dietary outliers": N10-4/20 and N10-4/33. N10-4/20 has a slightly higher δ^{15}N value than other VPLF individuals. Since N10-4/20 is between 18 and 20 months old, this sample's comparatively elevated δ^{15}N value likely represents consumption of breast-milk. The low δ^{15}N value of N10-4/33 was discussed previously (section 5.4) and she also has the lowest Postclassic tooth enamel $\delta^{18}O_p$ value, which falls just outside the Howie et al. (2010) baseline for Lamanai. Her bone $\delta^{18}O_p$ value falls within the middle of Lamanai's baseline range. It is possible that N10-4/33 was born in a different locality but at some point moved to and spent the last years of her life at Lamanai. Since her bone $\delta^{18}O_p$ values had time to adjust to the new locality, but her nitrogen-isotopic composition remains an outlier, it is possible that she was maintaining her traditional diet. Aside from these two outliers, however, there is no difference between the diet of the VPLF and other Postclassic individuals.

5.5.4   Other Markers of Geographic Identity

This study also briefly considered other lines of evidence that might provide insight into geographic identity, including cranial modification, dental modification, and grave goods. Cranial modification is a type of permanent body modification in which the skull of an individual is intentionally reshaped. This type of modification is done to infants and children by adults while their skull is still growing. Therefore, when making interpretations relating cranial modification to an individual's identity it is necessary to acknowledge that it represents the choices of the adults in their childhood, and may not reflect the modified individual's own values or identity at their time of death. While the motivations attributed to this practice range from beauty to group identity, in the Mesoamerican world it provides an indicator of geographic identity as there is often regional variation in "style" of cranial modification (Tiesler 2012).

At Lamanai the standard cranial modification is fronto-occipital, which is a form of the tabular oblique style (White 1996). Almost all VPLF burials for whom there is cranial shape information exhibit this Lamanero pattern. The only exception is N10-4/9A, who exhibits a lambdoidal flattening not found elsewhere at the site during the Postclassic (Howie et al. 2010; White 1996). She is also the previously mentioned individual whose

oxygen-isotope composition suggests that she was born elsewhere before moving to Lamanai. She also has dental modifications that are inconsistent with other individuals at the site (Howie et al. 2010).

Like cranial modification, intentional modification of teeth is also not only prevalent in Mesoamerica, but styles can also reflect regional preferences (Williams and White 2006). Unlike cranial modification, however, dental modification does not seem to be performed on children; there are almost no examples of dental modification in individuals younger than 15 and none in the Lamanai sample (Williams and White 2006). As the individuals are older, it is likely that they would have a say in the style of modification they received. Williams and White's (2006) study of a Postclassic sample of 61 adults from Lamanai reported that B4, C4, and C5 styles of dental modification (as defined by Romero) were the most common at Lamanai (Fig. 5.5-4). This pattern holds true for VPLF individuals. While B4 is the most common type of dental modification at other sites in Belize, C4 was relatively uncommon elsewhere (Williams and White 2006). The presence of C4 dental modifications on VPLF individuals strengthens the argument based on isotopic data that many of these individuals are local.
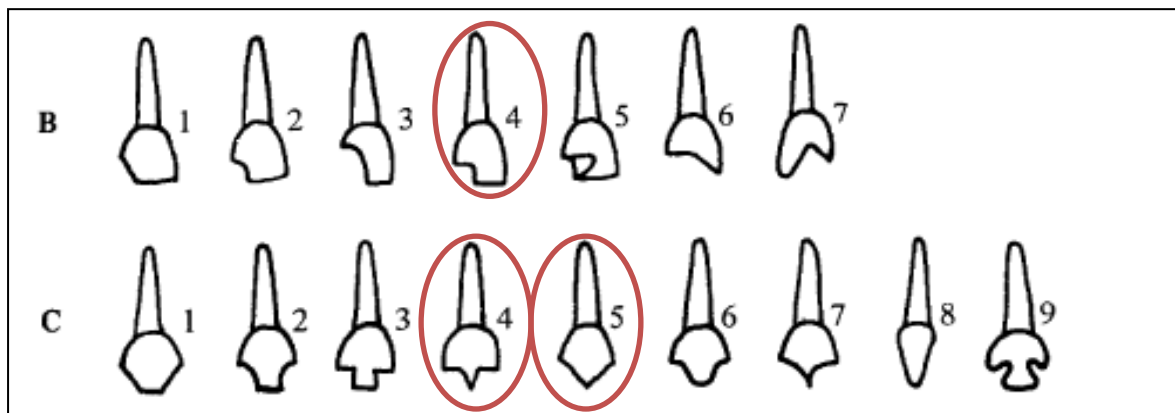
Figure 5.5-4 A portion of Romero's system of classification for dental modification styles with those most common at Lamanai highlighted. Revised from Williams and White (2006:140).

A brief survey revealed that the grave goods included with the VPLFs were extremely variable in type, material, and number (as is true of the other Postclassic burials). There was no single artifact or material class that showed up in all of the VPLF burials. Ceramics from 8 of these burials were previously examined in thin-section, and all are consistent with manufacture from locally available materials (Howie 2006a; 2012). Overall, there is no consistent inclusion of an item or material in these burials that distinguishes them from the other Postclassic burials or helps to explain a connection between them (geographic or otherwise).

5.5.5   Beyond "Non-locals"

At this point it is clear that the burials represent a range of individuals from different demographic groups, and although there may be some non-locals and/or immigrants buried in this position, they are in the minority. Thus it is necessary to look elsewhere for another explanation for the VPLF mortuary practice. Mortuary practice is strongly tied to ideology, particularly to understandings of death and the afterlife (Carr 1995). If the VPLFs do not represent a foreign practice brought and performed only by relocated individuals, this burial position might then indicate an ideological shift within at least part of Lamanai's population.

As mentioned in Chapter 3, there is already evidence of changes in ritual practice as the site transitions from the Terminal Classic into the Postclassic Period. This shows up in the ceramic record with the emergence of a wider range of incense burning paraphernalia and musical instruments (Howie 2006b). It is also seen in the construction of new areas for ceremonial activity and changes that indicate a possible shift to more public forms of ritual (e.g., shift from interior to exterior vessel decoration and less restrictive architecture in civic-ceremonial structures) (Andres 2005; Andres and Graham 2006; Howie 2006b).

As discussed in section 3.4.1, these changes also involve behaviours directly related to mortuary practices. One major trend was the increased interment of individuals within building cores and foundations, which also suggests an expansion of the function of some ceremonial buildings as they started to also act as "burial repositories" (Howie 2006a,

2012; Howie et al. 2010). A second major change was the introduction of the pattern of pre-interment breakage of ceramics (section 3.4.1). These two major shifts in funerary ritual during the transition from the Terminal Classic to Postclassic period make it clear that the appearance of the VPLF burial position was not a stand-alone change. Graham et al. (2013) suggests that these shifts in interment practices may reflect broader socio-cultural transformations, like those accompanying the appearance of "Christian" burials in the Historic period. As the VPLF position appears first on the coast during the Terminal Classic (albeit with some variation), it is possible that this shift in "worldview" affected the coastal communities before spreading to Lamanai (Graham et al. 2013). Regardless of where it may have originated and any associated broader societal change, there was a definite shift in mortuary practice and ritual, and thus likely related ideology at Lamanai involving a sizable portion of the Postclassic population.

In sum, one of the characteristics of the VPLF burials is variability, not only in the position itself, but also in the age, sex, status, and residential history of the people buried in this fashion. An ideological shift could crosscut these categories and there is already evidence of changes in ritual when this burial position emerges at the site. However, while this burial position was not uncommon at the site, it is important to emphasize that it occurred alongside other choices for mortuary treatment.

Chapter 6

6   Conclusions and Future Work

This study aimed to investigate mobility at Lamanai during the Postclassic and Historic periods. Along with considering how any observed mobility may tie into developments occurring within the wider Maya world, this study also explored whether there were any differences in residential history among individuals interred within different contexts (i.e., residential versus ceremonial structures) and if any sex- and/or age-related patterns of mobility were present. The VPLF burial position was also investigated, focusing particularly on whether this was restricted to non-locals and/or first generation immigrants or whether the appearance of this burial position at Lamanai was tied into other changes occurring at the site.

Similar to the results of the more temporally restricted study by Howie et al. (2010), the $\delta^{18}O_p$ values of this dataset are continuous, with essentially no identifiable outliers. The absence of clear outliers makes it difficult to identify non-local individuals. The differences in climate and physiography between northern Belize and other areas of Mesoamerica make it possible to identify geographically distant foreigners using oxygen isotope analysis. In contrast, the region surrounding Lamanai is climatically and physiographically much more uniform, which makes within-region mobility difficult to identify using oxygen-isotope data. Nonetheless, samples analyzed in this study do have a range of $\delta^{18}O_p$ values more than one and a half times larger than the expected ~ 2 ‰ intrapopulational variability in Mesoamerica (White et al. 1998; White et al. 2000; White, Spence et al. 2004; White, Storey et al. 2004) and there are several individuals identified in section 5.3.4 who likely experienced within-lifetime mobility. In sum, while there is some mobility reflected in this Lamanai sample, most of the movement likely occurred within the lowland region surrounding Lamanai, which agrees with the findings of Howie et al. (2010).

Lamanai had a long history as a thriving community, with a location that gave it access to both inland and coastal trade routes and lines of communication and connected it to

developments occurring beyond the site level. The growing recognition of the
Postclassic as a time characterized by increased interregional and international trade has
implications for the mobility of people. In the Historic period, the arrival and subsequent
actions of the Spanish precipitated considerable movement about the landscape. Dental
morphology studies suggest that the admixture seen at Lamanai during this time is
evidence of Lamanai accepting refugees (Jacobi 2000; Lang 1990). In both time periods,
the current study found evidence of individuals who likely moved between
geographically proximal areas with similar water isotopic compositions as Lamanai. In
the Historic period there is also statistically greater variation in tooth than bone $\delta^{18}O_p$
values, suggesting that there was more variation among individuals' childhood water
resources than in those being consumed during the years leading up to death. Perhaps
there was more variability in geographic origins than in their locations during the later
years of their life, which may be evidence of the acceptance of refugees or forcibly
relocated individuals during the Historic period at Lamanai.

To complicate matters, a downward shift in the mean $\delta^{18}O_p$ values of 0.6 ‰ for both
bone and tooth enamel was observed from the Postclassic to the Historic period (Figs.
5.3-1a, b). Although this difference is small when considering methodological error ($< \pm$
0.3 ‰), both tissues show the same shift, which does hint at an anthropologically
significant change. The two possible explanations, climate fluctuation or differential
mobility patterns, are not mutually exclusive and with the current data, no clear choice
between them is possible. To resolve this issue in the future, it would be ideal to have an
absolutely-dated, local high-resolution record of precipitation (e.g., stalagmite) in
conjunction with absolute dates on the individuals in question, or the inclusion of
additional lines of evidence to support movement of these individuals.

The difficulty in identifying non-locals and the lack of obvious foreigners limits
discussions exploring differences in mobility between sub-groups of Lamanai's burial
population. Nonetheless, some observations are possible concerning burial context, sex,
and age. This study found no evidence to suggest that the residential history of
individuals impacted their burial contexts, specifically their burial in
residential/administrative versus ceremonial structures. Both structure types contained

individuals who likely experienced within-lifetime movement, as well as individuals whose $\delta^{18}O_p$ values demonstrate little change. The bone and tooth $\delta^{18}O_p$ value averages for both structure types fall within Lamanai's baseline, which suggests that some of the individuals had $\delta^{18}O_p$ values local to Lamanai. However, both structure types had ranges of tooth $\delta^{18}O_p$ values closer to 3 ‰ than the 2 ‰ expected for intrapopulational variability in Mesoamerica. This result suggests that there are individuals within each structure type who did not spend portions of their childhood at the same location as each other. In combination, these observations suggest that at least some of the individuals were not locally born, and therefore, that non-locals were not excluded from burial in either structure type.

Turning to the question of sex-related patterns of mobility, Postclassic period females exhibit much larger differences between their enamel and bone $\delta^{18}O_p$ values than males. This could indicate greater within-lifetime mobility for females than males, or that female within-lifetime movement, relative to males, involved relocations between areas of greater geographic, climatic, and/or physiographic difference. However, the Postclassic period's pattern of both consistent mid-size to large $|\Delta^{18}O_{p\ enamel-bone}|$ in females and generally small $|\Delta^{18}O_{p\ enamel-bone}|$ for males is not seen in the Historic period. Overall, there is more variation in male than female bone $\delta^{18}O_p$ values, suggesting that adult males were exposed to a wider variety of drinking water sources or engaged in more mobility as adults (possibly through travel or relocation), particularly in the Historic period. The Historic period range of bone $\delta^{18}O_p$ values suggests that not all Historic males spent their last years living in the same location as each other. Although males exhibited more variability than females as adults, the opposite pattern is seen in infancy/childhood. The larger range of Historic female enamel $\delta^{18}O_p$ values suggests that they were not all born and/or spent their childhood at the same location. This, along with values of $|\Delta^{18}O_{p\ enamel-bone}|$, may suggest a partial continuation of the observed Postclassic female mobility pattern.

Two weak patterns in oxygen-isotope compositions were observed that may be related to age. The first is that the average tooth enamel $\delta^{18}O_p$ value for juveniles 2.5/3 to 7/8 years old (M2s) is higher than the enamel composition of individuals from birth to 2.5/3 years

old (M1s). This difference may partly represent an uncorrected breastfeeding effect in the M2s. However, it could also be a result of the sample-size discrepancy between the tooth types, as there are six times as many samples of M1s as M2s. The second pattern is that for the Historic period, on average, bone $\delta^{18}O_p$ values of Juveniles are higher than Adults. This difference may also indicate a breastfeeding effect, but again, the sample size is very small. In the future a larger sample of M2s and juvenile bone would help to resolve these questions, possibly in the context of a more targeted study investigating breastfeeding/weaning at Lamanai.

This study also used evidence of geographic identity in order to better understand the appearance of the VPLF burial position at the site. The oxygen-isotope data for the VPLFs demonstrate that although there is some evidence of relocation, the majority of the individuals are likely local to Lamanai or its surrounding area. The diet data, obtained from carbon and nitrogen isotopic analysis of collagen, indicate that the VPLF individuals consumed a similar diet as the rest of the Postclassic individuals. Other lines of evidence also do not indicate a strong non-local presence within this group. Almost all of the VPLF individuals with cranial modification exhibit the standard Lamanero appearance. The dental modifications also seem consistent with not only Belize, but with Postclassic Lamanai styles. In addition, there was no obvious patterning in the grave goods, aside from the Postclassic pattern of variability.

What emerges from this study's exploration of Lamanai's VPLF individuals is that variability is one of the characteristics of these burials. This variability is seen not only in the position itself (particularly in the placement of the arms), but also in the individuals buried in this fashion, as reflected by age, sex, status, and residential history. The emergence of this position may be related to an ideological shift. This is an explanation that would crosscut so many categories of people – and there is already evidence of changes in ritual at the site during the time when this burial position emerges. However, it is important to note that VPLF burials occurred alongside other choices for mortuary treatment.

While this study made steps towards moving beyond the descriptive, as is the current push in bioarchaeology (Joyce 2005; Knudson and Stojanowski 2009; White et al. 2009), future work on the VPLF individuals and their contemporaries has the potential to further improve our understanding. Incorporation of additional lines of evidence (e.g. markers of physical activity) and/or approaching Lamanai's burials from a phenomenological perspective of lived experiences with a focus on embodiment (Csordas 1990; Joyce 2005) might not only benefit the understanding of the VPLF position, but also help us to better understand the lives of all Lamaneros represented in the burial population.

In the process of tackling the primary goals of this study, isotopic data for Lamanai-area water sources and dietary data were also produced. The preliminary Lamanai-area local meteoric water line (y = 7.7467x + 7.3151) and oxygen- and hydrogen-isotope results (Appendix B) add to the limited water isotopic data previously available for this area. Multi-year monthly sampling of Lamanai's lagoon water, groundwater, and precipitation would be useful for establishing a better modern baseline for the site.

The carbon- and nitrogen-isotope bone-collagen results from this study add to the previously available dietary data for Lamanai, particularly for the Historic period. The data presented here are in general agreement with previous studies of Lamanai, which show very little change in diet between the Postclassic and Historic periods (Coyston et al. 1999; White and Schwarcz 1989), although there is the possibility of a very slight ^{15}N-enrichment in the Historic over the Postclassic period. Future research on diet at Lamanai could include determination of δ^{13}C from the structural carbonate of this study's individuals (particularly in the Historic period to bolster the current n = 10 from Coyston et al. 1999). These data can be used in combination with the collagen diet data for more complex modeling of overall diet, as collagen reflects only the protein component of the diet while carbonate reflects whole diet. Carbon- (both from collagen and carbonate) and nitrogen-isotope analysis of archaeological fish remains from Lamanai may also help in dietary interpretations at Lamanai and other Belizean sites. There are not many geographically relevant published studies of fish remains (particularly archaeological fish remains). As discussed in Chapter 2, in order to properly interpret human paleodiet

isotopic data it is important to know the carbon and nitrogen isotopic compositions of local resources.

In conclusion, it appears that most of the mobility exhibited by this sample of Lamanai's burial population during the Postclassic and Historic periods did not extend beyond the surrounding lowland area. This does not mean that Lamanai did not host long-distance travelers and foreign dignitaries or that Lamaneros were not making long journeys themselves. As bone averages input over many years, evidence of journeys (even long ones) may be obscured, and visitors (as opposed to immigrants) would not likely end up in Lamanai's burial population. This study adds to the body of literature about Lamanai, but there is still work to be done to understand how this long-surviving, lagoon-side site and its populace fit into the larger Mesoamerican world.

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Appendices

Appendix A - Age, Sex, and Burial Information of Individuals in this Study

	Individual	Sex*	Age	Orien-tation	DM†	CM‡	VPLF?	Full Body Position Description	Associated Artifacts
Postclassic Period	N10-1/2	1	~ 50		1	1			
	N10-12/6a	1	old adult (over 45)	head South; 20˚E	0	1	Yes	"extended (face down) /w legs bent up over back ("Diving Burial")"	>200 drilled marginella shells; drilled bone bead; 49Spondylus beads; 5 cowry shells; pottery including Buk Chalice, Frying pan censer, stuccoed effigy dish, daylight darknight dish, orange flaring tripod dishes, and Buk urns
	N10-12/8	1		head W; 300˚	0	1	Yes	"'Frog' - legs bent back with some lower leg collapse to the north; feet are over buttocks; arms bent at elbow with hand resting under left shoulder & directly below chin"	LA1896/1-11 & 1716/1; 1 chalice; 1 incised bowl; 1 courseware jar; 1 frying pan censer handle with part of dish attacked alongside right arm; some ceramics underlay left leg and most others overlay left arm
	N10-2/14	2	adult	"head N 27˚, facing down and slightly to the R"	0	0	Yes	"*frogged*, with R leg loosely doubled with foot atop L leg (failure in binding body?), arms at sides"	none
	N10-2/16	1	20-40	"head E 91˚, facing down (head canted slightly to R)"	1	0	Yes	"*frogged*, hands under pelvis, feet at R side of pelvis"	118/1 - 9; ceramics (likely pre-inhumation breakage), needles, pin or awls, oliva beads, obsidian blade
	N10-2/20B	1	40-50	"head N 8˚, facing down"	2	0	Yes	"probably *frogged*, with arms bent at elbows and lower arms on back; legs apparently displaced"	"127/1 jar, primarily W of skull of Individual A; all remaining vessels smashed prior to inhumation and spread over and around the bodies; 127/2 et seq."; ~ 15 vessels
	N10-2/21	0	12-14 yr	head W 265˚, facing 213˚	0	1	Yes	"*frogged*, skull twisted sharply up and to L, so as to rest on hand"	"128/1 jar, handled, at S side of body, pre-inhumation breakage"

Source: Burial information obtained primarily from Dr. David Pendergast's unpublished field notes. Age estimation and sex determination performed by Dr. Hermann Helmuth and/or Dr. Christine White.

Note: In Pendergast's field notes, the term "frog" or "frogged" is used to refer to what this thesis calls the VPLF position.

* Sex: 0 = Unknown, 1 = Male, 2 = Female, 3 = Probable Male, 4 = Probable Female.

† DM = Dental Modification: 0 = Unknown, 1 = Present, 2 = Absent.

‡ CM = Cranial Modification: 0 = Unknown, 1 = Present, 2 = Absent.

	Individual	Sex*	Age	Orientation	DM†	CM‡	VPLF?	Full Body Position Description	Associated Artifacts
Postclassic Period	N10-2/22	1	over 30; adult	"head SW 201°, facing 295° and slightly downward"	1	1	Yes	"*frogged*, slightly tilted up to the R, with R arm in tight flex, L under chest with hand at sharp angle downward towards pelvis, feet on pelvis"	"130/1 bead, stone, at face (possibly originally in mouth?)"
	N10-2/23	1	over 60; adult +	"head S 190°, facing about 73°"	1	1	No	"dorsal, partially extended, arms slightly akimbo at sides, legs flexed with feet at pelvis"	"131/1 group of shells, perforated, at W side of grave more or less opposite L elbow; 131/2 deer ulna awl, under skeleton; 131/3 smaller double hand drum, orange - smashed and scattered with /4 and /5 at E side of grave; 131/4 larger double hand drum, orange; 131/5 olla unslipped"
	N10-2/24	3	over 40	"head N 22°, facing up and S"	2	0	Yes	"dorsal, probably fully extended, arms flexed to L side"	none
	N10-2/4 A	4	14-18	head NW 302°, facing down	2	0	Yes	"ventral, hands under chest, legs bent back at knees with feet atop pelvis ('*frogged*')"	"44/1 jar, red, incised decoration, part NW of head, part at R arm, remainder atop back & L arm; 44/2 stone, plano-convex, ovoid, at R side of pelvis; 44/3 hammerstone, between knees; 44/4 Oliva shell, on stones atop L elbow; 44/5 obsidian flake blade, fragmentary, with fragments of 44/1 at R side of head"
	N10-2/40	2	45-55; ~ 50	"head S 202°, facing W and down"	1	1	Yes	"*frogged*, arms at sides, feet on pelvis"	"165/1+ group of vessels smashed and spread over back; number to be determined in lab"
	N10-2/44	0	~ 8 yr	head SSW 202°, facing down	0	1	Yes	"*frogged*, arms bent with L hand beneath abdomen, R hand under L chest, feet more or less on pelvis"	175/1 & 2 pendants "jade, reworked from a larger object, above burial; 175/3 pendant, shell, with /1 and /2; /4 dish, flaring-side, scattered over burial"
	N10-2/50	0	6-7		2	0	No	flexed	none
	N10-3/4	1	adult		0	0			

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	Individual	Sex*	Age	Orien-tation	DM†	CM‡	VPLF?	Full Body Position Description	Associated Artifacts
Postclassic Period	N10-4/10	1	15-20	"(body curved southward) main body WNW 291°, head SW 247°, facing down and SE 153°"	1	0	Yes	"*frogged*, hands under pelvis"	"73/1 dish or bowl, outcurving-side, redware, Tulum-related; at L hip, pre-inhumation breakage; 73/2 Marginella beads, single punched body perforation, total 22; scattered with /1 at feet and L leg with one at skull; 73/3 portion of obsidian flake blade, beneath torso; possibly a chance inclusion"
	N10-4/11	2	~ 30 or over	"head WNW 296°, facing down and N"	1	0	Yes	"*frogged*, with arms slightly bent inward; feet probably originally on pelvis. Body somewhat curved and irregularly placed owing to the stone bedding, with legs much lower than head"	"74/1 blade, chert; above burial, but probably associated"
	N10-4/16	1	over 50	"head WNW 293°, facing down"	2	0	Yes	"*Frogged*, arms at sides"	none listed
	N10-4/19 A	4	adult		1	1			
	N10-4/21	1	adult under 40		2	0	No	"skull at S and below limbs and ribs, with ribs scattered N or limb bones"; secondary burial	83/1 bowl, Tulum-style incised decoration, all pieces inverted, possibly pre-inhumation breakage; 83/2 bowl, main portion beneath skull of Burial 19;"relationship between burials 19 and 21 is not entirely clear"
	N10-4/22	2	mature adult	"head SSE 201°, facing down"	1	0	Yes	"*frogged*, arms at sides with R hand beneath pelvis and L hand at L hip"	"85/1 dish, outcurving-side, tripod, part inverted over L shoulder, amongst rocks, with large rocks beneath the vessel portion, with remaining portions over mid-body and an additional piece E of the skull; pre-inhumation breakage"

Source: Burial information obtained primarily from Dr. David Pendergast's unpublished field notes. Age estimation and sex determination performed by Dr. Hermann Helmuth and/or Dr. Christine White.

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	Individual	Sex*	Age	Orien-tation	DM†	CM‡	VPLF?	Full Body Position Description	Associated Artifacts
Postclassic Period	N10-4/26	1	over 30	"head WNW 284˚, facing down and NE"	2	0	Yes	"*frogged*, arms at sides with R hand at hip and L arm bent at elbow with hand under pelvis. Head turned to R"	"89/1 dish, outcurving-side, tripod, on edge W of skull with top towards skull; in situ breakage; 89/2 Marginella shells, total 10, just N of R shoulder; 89/3 freshwater mussel shell single valve, interior down on knee; 89/4 dish, outcurving-side, tripod, fragmentary"
	N10-4/27B	0	adult	"head SW 296˚, probably facing down"	2	0	Yes	"*frogged*, the one remaining arm (L) bent at elbow (lower arm and hand only), hand at right angle with arm, atop lower back"	none listed
	N10-4/28	1	old adult	"head WNW 292˚, facing down"	1	0	Yes	"*frogged*, arms tightly flexed with hands at shoulders"	90/1-24 including ceramics with pre-inhumation breakage, animal jaw, mirror, shell and jade disc beads, copper button-shaped (Monte Alban form) ornaments, human tooth beads, carved bone representations of human fingers
	N10-4/31	0	18-21	"head S 183˚, facing E 86˚"	1	0	Yes	"*frogged*, arms probably at sides"	"93/1 dish, outcurving-side, tripod, Tulum-style feet, inverted 9 cm above L elbow; apparently in situ breakage, but incomplete"
	N10-4/33	2	30-40	"head NE 11˚, facing down"	2	0	Yes	"*frogged* (feet probably on pelvis), arms more or less at sides"	"97/1 sherd mass, or possibly a vessel, W of L leg, 0-10 cm above leg"
	N10-4/42	2	~ 20	"head SE 136˚, facing ca 255˚"	2	2	No	"tight flex on side"	"144/1 bone disc (spindle whorl?), at feet; sherds of a number of vessels were massed at the feet"
	N10-4/44	1	mature adult	"head N 5˚, facing down and to R"	0	0	Yes	"*frogged* variant; ventral, arms akimbo with R hand under pelvis, L at legs. Legs flexed with knees to L side, feet at pelvis"	none listed

Source: Burial information obtained primarily from Dr. David Pendergast's unpublished field notes. Age estimation and sex determination performed by Dr. Hermann Helmuth and/or Dr. Christine White.

Note: In Pendergast's field notes, the term "frog" or "frogged" is used to refer to what this thesis calls the VPLF position.

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Period	Individual	Sex*	Age	Orien-tation	DM†	CM‡	VPLF?	Full Body Position Description	Associated Artifacts
Postclassic Period	N10-4/45	1	30+	"head N 16˚, facing"	1	0	Yes	"*frogged*, arms at sides, slightly bent at elbows, hands under pelvis"	246/1-7 including a whole jar atop skull, ceramics with pre-inhumation breakage, a shell ornament west of the hips, and a lamina of pyrite atop the thoracic vertebrae
	N10-7/1	2	45+		2	0			"8 vessels, including elaborate censers; 46 irreg. pcs. of obsidian; 1 Oliva bead; 1 bone pin or awl"
	N10-9/1	0	9 mo-1 yr		0	0			none
	N10-9/10	1	30-40		2	0			"3 vessels, including censer and elaborate bowl, 2 bone pins (one a human fibula), 1 carved jade pendant"
	N10-9/2	0	2		0	0			none
	N10-9/6	0	5-6		0	0			
	N11-5/7A	1	40+		2	2	No	seated	copper tweezers, shell horse-collar ornament (individual was the male of "Loving Couple" see Pendergast 1989 and White et al. 2009 for more details)
	N11-5/7B	2	30-35		2	2	No	seated, arm around shoulders of N11-5/7A	5 copper-tin hair rings (individual was the female of "Loving Couple" see Pendergast 1989 and White et al. 2009 for more details)
	N12-11/4B	2	40-50		2	2			
	N12-11/5 A	2	20-25		0	2			
	N12-11/GP 19	1	20-25		0	0			
Historic Period	YDL I - 85 - 11	0	1-2 yr		0	0			
	YDL I - 85- 17	2	20-40; 20-35		0	2			
	YDL I - 85 - 1a	2	adult; 20-35 yr max.		0	1			
	YDL I - 85 - 23	2	20-30; 20-35		2	0			
	YDL I - 85 - 25	2	adult; 20+		2	0			
	YDL I - 85 - 27	2	20-30		0	0			

Source: Burial information obtained primarily from Dr. David Pendergast's unpublished field notes. Age estimation and sex determination performed by Dr. Hermann Helmuth and/or Dr. Christine White.

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‡ CM = Cranial Modification: 0 = Unknown, 1 = Present, 2 = Absent.

	Individual	Sex*	Age	Orien-tation	DM†	CM‡	VPLF?	Full Body Position Description	Associated Artifacts
Historic Period	YDL I - 85 - 29	1	20+		0	0			
	YDL I - 85 - 3	4	40+; 35-50		0	1			
	YDL I - 85 - 37	0	max. 2 yrs		0	0			
	YDL I - 85 - 6	2	20-40; over 20		2	0			
	YDL I - 85 - 62	2	20-35; 20-25		0	2			
	YDL I - 85 - 64	4	adult; 50+		2	2			
	YDL I - 85 - 66	1	30-35		0	2			
	YDL I - 85 - 70	1	20+; 30-40		0	2			
	YDL I - 85 - 73	1	adult; 20-35		2	2			
	YDL I - 85 - 74	1	20-30; 20+		2	0			
	YDL I - 85 - 81	2	35-50		0	0			
	YDL I - 85 - 82 c	0	5-8 yr		0	0			
	YDL I - 85 - 83	1	30+		0	2			
	YDL I - 85 - 85	1	35-50		0	1			
	YDL I - 85 - 86	1	~ 25 yr		0	0			
	YDL I - 85 - 89	1	25-35; 25-30		0	2			
	YDL I - 85 - 97	1	25-30		0	2			
	YDL I - 85 - 99	0	4-5 yr		0	0			

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Appendix B - Water Samples with δ^{18}O and δ^2H Data for Each Analysis

#	Collector/Researcher	Description	Location	Date Collected	*	δ^{18}O /‰	*	δ^{18}O /‰	*	δ^{18}O /‰	*	δ^2H /‰	*	δ^2H /‰	*	δ^2H /‰	*	δ^2H /‰	*	δ^2H /‰	Comments
2	Alicia Donis	Pond	Indian Creek, Lamanai, Belize	May 17/08	GB	-4.6	Pi	-4.6			Zn	-24	Pi	-27							
3	Alicia Donis	New River Lagoon (lake)	Lamanai	May 18/08	Pi	-1.3					Zn	-11	Pi	-7							
5	Alicia Donis	rain water	Indian Church, Lamanai, Belize	May 25/08	Pi	-0.3					Zn	-3	Pi	1							
6	Alicia Donis	stream	Indian Creek-Weibe Land, Lamanai, Belize	May 28/08	GB	-4.3															
7	Alicia Donis	rain water	Indian Church, Lamanai, Belize	May 29/08	Pi	-1.3					Zn	-4	Pi	0	Pi						
8	Alicia Donis	rain water	Indian Church, Lamanai, Belize	May 30/08	Pi	-15.6	Pi	-15.5			Zn	-119	Zn	-120	Pi	-115	Pi	-115	Zn	-120	
9	Alicia Donis	rain water (Tropical Storm Arthur)	Indian Church, Lamanai, Belize	May 30/08	Pi	-15.7					Zn	-120	Zn	-108	Zn	-112	Zn	-114	Pi	-111	
10	Alicia Donis	rain water (Tropical Storm Arthur)	Lamanai, Belize	June 2/08	Pi	-10.5					Zn	-73	Zn	-75	Pi	-72					
11	Alicia Donis	Groundwater (Well 1)	Indian Church, Lamanai, Belize	June 4/08	Pi	-3.5					Zn	-21	Pi	-24							
12	Alicia Donis	Groundwater (Well 2)	Indian Church, Lamanai, Belize	June 4/08	Pi	-5.8					Zn	-38	Zn	-40	Pi	-36					
14	Alicia Donis	rain water	Indian Church, Lamanai, Belize	June 10/08	Pi	-4.3					Zn	-31	Zn	-28	Pi	-29					

*These columns indicate which method was used to obtain the δ-value immediately to the right. See Chapter 4 for the explanation of these methods: Zn = Zinc; Pi = Picarro; GB = Gas Bench.

#	Collector/ Researcher	Description	Location	Date Collected	*	$\delta^{18}O$ /‰	*	$\delta^{18}O$ /‰	*	$\delta^{18}O$ /‰	*	δ^2H /‰	*	δ^2H /‰	*	δ^2H /‰	*	δ^2H /‰	*	δ^2H /‰	Comments
15	Alicia Donis	rain water	Indian Church, Lamanai, Belize	June 11/08	GB	-4.1	Pi	-3.6	Pi	-4.0	Zn	-22	Zn	-27	Pi	-21	Pi	-20			
16	Alicia Donis	fresh water spring	Indian Church/San Carlos, Lamanai, Belize	June 12/08	Pi	-3.3					Zn	-23	Zn	-24	Pi	-20					same spring as 17
17	Alicia Donis	fresh water spring	Indian Church/San Carlos, Lamanai, Belize	June 12/08	Pi						Zn	-20	Zn	-27							
19	Alicia Donis	Tilapia pond	Indian Church/San Carlos, Lamanai, Belize	June 12/08	Pi	-6.4	Pi	-6.3			Zn	-52	Zn	-46	Pi	-46	Pi	-47			
18	Alicia Donis	Barber Creek (endpoint of creek)	Lamanai, Belize	June 13/08	Pi	-3.5					Zn	-21	Zn	-25	Zn	-24	Zn	-26	Pi	-22	18 & 20 same point same time
20	Alicia Donis	Barber Creek (endpoint of creek)	Lamanai, Belize	June 13/08	Pi	-3.4					Zn	-25	Zn	-23	Pi	-22					
22	Alicia Donis	Barber Creek (midpoint of creek)	Lamanai, Belize	June 13/08	Pi	-3.4					Zn	-20	Pi	-20							22 & 23 same point same time
23	Alicia Donis	Barber Creek (midpoint of creek)	Lamanai, Belize	June 13/08	GB	-3.5	GB	-3.5	Pi	-3.6	Zn	-25	Pi	-21							

*These columns indicate which method was used to obtain the δ-value immediately to the right. See Chapter 4 for the explanation of these methods: Zn = Zinc; Pi = Picarro; GB = Gas Bench.

#	Collector/Researcher	Description	Location	Date Collected	*	δ^{18}O /‰	*	δ^{18}O /‰	*	δ^{18}O /‰	*	δ^{2}H /‰	*	δ^{2}H /‰	*	δ^{2}H /‰	*	δ^{2}H /‰	*	δ^{2}H /‰	Comments
24	Alicia Donis	Barber Creek/New River (river)	Lamanai, Belize	June 13/08	Pi	-3.5					Zn	-24	Zn	-20	Pi	-22					24 & 25 same point same time
25	Alicia Donis	Barber Creek/New River (river)	Lamanai, Belize	June 13/08	Pi	-3.2					Zn	-27	Zn	-22	Pi	-22					
26	Alicia Donis	"Marcus Creek" (endpoint of slow moving pond)	Lamanai, Belize	June 13/08	Pi	-3.3					Zn	-22	Zn	-24	Zn	-21	Pi	-22			
21	Alicia Donis	Marcus Creek" (midppoint)	Lamanai, Belize	June 13/08	Pi	-3.4					Zn	-22	Zn	-21	Pi	-21					
27	Alicia Donis	"Marcus Creek"/New River (river)	Lamanai, Belize	June 13/08	Pi	-3.1					Zn	-25	Zn	-24	PI	-21					
28	Alicia Donis	New River Lagoon (lake)	Lamanai, Belize	June 13/08	GB	-3.5	Pi	-3.6			Zn	-21	Pi	-22							
29	Alicia Donis	New River Lagoon (lake)	Lamanai, Belize	June 13/08	GB	-3.6	Pi	-3.4			Zn	-19	Zn	-22	Pi	-21					
30	Alicia Donis	"Lake Ontario" (pond)	Indian Creek-Weibe Land, Lamanai, Belize	June 13/08	GB	-5.2	Pi	-5.2			Pi	-40	Pi	-39							
32	Alicia Donis	Jorge's Pond (groundwater pond)	Indian Creek, Lamanai, Belize	June 14/08	Pi	-4.2					Pi	-28									
31	Alicia Donis	Groundwater (Well 2)	Indian Church, Lamanai, Belize	June 14/08	Pi	-4.7					Zn	-27	Zn	-30	Pi	-26					

*These columns indicate which method was used to obtain the δ-value immediately to the right. See Chapter 4 for the explanation of these methods: Zn = Zinc; Pi = Picarro; GB = Gas Bench.

#	Collector/Researcher	Description	Location	Date Collected	*	δ^{18}O /‰	*	δ^{18}O /‰	*	δ^{18}O /‰	*	δ^{2}H /‰	*	δ^{2}H /‰	*	δ^{2}H /‰	*	δ^{2}H /‰	*	δ^{2}H /‰	Comments
34	Alicia Donis	New River Lagoon (lake)	Lamanai South Lodge, Belize	June 14/08	GB	-3.4	Pi	-3.3			Zn	-20	Zn	-20	Zn	-23	Pi	-20			
1	Ruben/ Alicia Donis	Lagoon	Lamanai Archaeological Reserve, Belize	Jul-08	Pi	-4.5					Pi	-30									
2	Ruben/ Alicia Donis	Lagoon	Lamanai Archaeological Reserve, Belize	Aug-08	Pi	-3.5					Pi	-24									
3	Ruben/ Alicia Donis	Lagoon	Lamanai Archaeological Reserve, Belize	Sep-08	Pi	-2.4					Pi	-18									
4	Ruben/ Alicia Donis	Lagoon	Lamanai Archaeological Reserve, Belize	Oct-08	Pi	-2.9					Pi	-20									
6	Ruben/ Alicia Donis	Lagoon	Lamanai Archaeological Reserve, Belize	Dec-08	Pi	-5.4					Pi	-31									
7	Ruben/ Alicia Donis	Lagoon	Lamanai Archaeological Reserve, Belize	Jan-09	Pi	-3.2					Pi	-21									
8	Ruben/ Alicia Donis	Lagoon	Lamanai Archaeological Reserve, Belize	Feb-09	Pi	-3.3					Pi	-21									
9	Ruben/ Alicia Donis	Lagoon	Lamanai Archaeological Reserve, Belize	Mar-09	Pi	-3.2					Pi	-20									

*These columns indicate which method was used to obtain the δ-value immediately to the right. See Chapter 4 for the explanation of these methods: Zn = Zinc; Pi = Picarro; GB = Gas Bench.

#	Collector/ Researcher	Description	Location	Date Collected	*	$\delta^{18}O$ /‰	*	$\delta^{18}O$ /‰	*	$\delta^{18}O$ /‰	*	$\delta^{2}H$ /‰	*	$\delta^{2}H$ /‰	*	$\delta^{2}H$ /‰	*	$\delta^{2}H$ /‰	*	$\delta^{2}H$ /‰	Comments
13	Ruben/ Alicia Donis	Well 3	Indian Church Village, Belize	Jul-08	Pi	-4.2					Pi	-26									
14	Ruben/ Alicia Donis	Well 3	Indian Church Village, Belize	Aug-08	Pi	-4.3					Pi	-27									
15	Ruben/ Alicia Donis	Well 3	Indian Church Village, Belize	Sep-08	Pi	-4.4		-4.5			Pi	-26	Pi	-27							
16	Ruben/ Alicia Donis	Well 3	Indian Church Village, Belize	Oct-08	Pi	-4.5					Pi	-26									
18	Ruben/ Alicia Donis	Well 3	Indian Church Village, Belize	Dec-08	Pi	-4.7					Pi	-28									
19	Ruben/ Alicia Donis	Well 3	Indian Church Village, Belize	Jan-09	Pi	-5.2					Pi	-31									
20	Ruben/ Alicia Donis	Well 3	Indian Church Village, Belize	Feb-09	Pi	-4.7					Pi	-30									
21	Ruben/ Alicia Donis	Well 3	Indian Church Village, Belize	Mar-09	Pi	-4.9					Pi	-29									
22	Ruben/ Alicia Donis	Well 3	Indian Church Village, Belize	Apr-09	Pi	-4.9					Pi	-29									
4	Linda Howie	Spring flowing into lagoon	Indian Church Beach, Lamanai, Belize	July 5/09	Pi	-3.5					Zn	-16	Pi	-20							
6	Linda Howie	spring	1 mile south of Indian Church Beach, Lamanai, Belize	July 5/09	Pi	-4.2					Zn	-22	Pi	-23							

*These columns indicate which method was used to obtain the δ-value immediately to the right. See Chapter 4 for the explanation of these methods: Zn = Zinc; Pi = Picarro; GB = Gas Bench.

#	Collector/ Researcher	Description	Location	Date Collected	*	$\delta^{18}O$ /‰	*	$\delta^{18}O$ /‰	*	$\delta^{18}O$ /‰	*	$\delta^{2}H$ /‰	*	$\delta^{2}H$ /‰	*	$\delta^{2}H$ /‰	*	$\delta^{2}H$ /‰	*	$\delta^{2}H$ /‰	Comments
5	Linda Howie	spring	150m south of Indian Church Beach, Lamanai, Belize	July 5/09	Pi	-4.6					Zn	-21	Pi	-25							
7	Linda Howie	spring	Indian Church, Lamanai, Belize	July 5/09	Pi	-4.6					Zn	-26	Zn	-26	Pi	-27					

*These columns indicate which method was used to obtain the δ-value immediately to the right. See Chapter 4 for the explanation of these methods: Zn = Zinc; Pi = Picarro; GB = Gas Bench.

Appendix C - $\delta^{18}O_p$, $\delta^{13}C$, and $\delta^{15}N$ Values and Diagenesis Data

Individual		Element	$\delta^{18}O_p$ /‰[a]	CI	C/P	FTIR peak?[b]	CO$_2$ Yield[c]	Ag$_3$PO$_4$ Yield[d]	$\delta^{13}C$ /‰	$\delta^{15}N$ /‰	C:N	Collagen % Yield[d]
N10-1/2		Bone		3.32	0.26	1096						0.07
		M1	18.6	2.90	0.29	No	4.88	1.56				
N10-12/6a		M2	20.8	2.71	0.31	No	4.86	1.02				
N10-12/8		Bone	18.5	3.16	0.28	No	4.71	1.35	**-8.3**	**8.1**	**3.22**	**2.70**
		M1	18.1	2.55	0.38	No	4.88	1.49				
N10-2/14		Bone	18.0	3.22	0.26	No	4.92	1.37	-8.2	8.7	3.23	3.45
N10-2/16		Bone		3.33	0.23	No						0.89
		M1	**20.9**	2.60	0.39	No	**4.85**	**1.37**				
		M2	19.7	2.48	0.43	No	4.80	1.36				
N10-2/20B		Bone	19.7	2.75	0.43	No	4.81	0.93				
		PM	19.6	2.49	0.44	No	4.95	1.51				
N10-2/21		Bone	17.5	2.74	0.36	No	4.80	1.30	-8.1	8.7	3.26	4.68
		M1	20.0	2.51	0.41	No	4.98	1.42				
		M2	18.8	2.93	0.27	No	4.80	1.32				
N10-2/22 *		Bone	**17.5**	**2.72**	**0.39**	No	**4.99**	**1.25**	-7.7	9.3	3.22	3.10
	A	M1	19.3	2.45	0.41	No	4.88	1.34				
	B	M1	19.2	2.66	0.36	No	4.85	1.46				
N10-2/23		Bone	18.6	2.75	0.38	No	4.97	0.82				
N10-2/2		Bone	19.5	2.98	0.41	No	4.85	1.12				
		M1	18.1	2.67	0.34	No	4.76	1.51				
N10-2/4 A		Bone		2.73	0.36	No						0.57
		M2	**20.0**	2.51	0.42	No	**4.82**	**1.47**				
N10-2/40		Bone	17.5	2.84	0.34	No	4.77	1.25				
		M1	19.9	2.38	0.47	No	5.00	1.51				
N10-2/44		Bone	17.5	2.89	0.39	No	4.78	1.33	-9.2	7.8	3.23	9.39
		M2	19.6	2.47	0.4	No	4.76	1.36				
N10-2/50		Bone	18.4	2.99	0.41	No	4.99	1.31				
		M1	19.1	**2.85**	**0.31**	No	4.80	1.61				
N10-3/4		Bone	19.0	2.98	0.39	No	4.83	1.32				
		M1	**20.3**	2.75	0.33	No	**4.88**	**1.49**				
N10-4/10		Bone	17.8	2.66	0.47	No	4.67	1.26	-9.4	9.2	3.23	6.61
		M1	19.4	2.67	0.32	No	4.86	1.61				

* There were two different jaws assigned to the same individual, as it was unclear which was the reported VPLF individual, a tooth from both jaws were sampled.

Note: Values in boldface font represent averages.
[a] None of these $\delta^{18}O_p$ values currently have the breastfeeding adjustments applied.
[b] This column indicates whether a peak was present at 710 cm^{-1} (calcite) or 1096 cm^{-1}
(francolite/fluorapatite) on the FTIR spectrum at 1 ‰ sensitivity using the OPUS NT peak-pick function.
[c] μmol/mg Ag$_3$PO$_4$
[d] mg produced/mg sample

Individual	Element	$\delta^{18}O_p$ /‰[a]	CI	C/P	FTIR peak?[b]	CO_2 Yield[c]	Ag_3PO_4 Yield[d]	$\delta^{13}C$ /‰	$\delta^{15}N$ /‰	C:N	Collagen % Yield[d]
N10-4/11	Bone	**18.6**	2.79	0.37	No	**4.89**	**1.02**				
	M1	20.6	2.52	0.39	No	4.83	1.21				
N10-4/16	M1	20.4	2.55	0.37	No	4.98	1.01				
N10-4/19 A	Bone	17.5	2.70	0.45	No	4.85	1.28				
	M1	19.3	2.68	0.4	No	4.88	1.60				
N10-4/21	Bone	**18.1**	2.91	0.39	No	**5.08**	**1.31**				
	M1	19.4	2.57	0.42	No	4.80	1.55				
N10-4/22	Bone	**18.3**	2.84	0.35	No	**5.00**	**1.22**	-8.9	9.1	3.24	4.45
	PM	20.0	2.80	0.31	No	4.82	1.14				
N10-4/26*	Bone	19.7	3.09	0.32	No	4.91	0.94				**0.37**
	M2	19.8	2.53	0.38	No	4.70	1.52				
N10-4/27B	Bone	17.4	2.83	0.4	No	4.91	1.38	-8.9	10.2	3.21	12.64
N10-4/28	Bone	**17.9**	3.26	0.25	No	**5.04**	**1.33**	-8.9	9.1	3.25	1.81
N10-4/31	Bone	19.5	2.73	0.36	No	4.99	1.02				
	PM	19.0	**2.78**	**0.29**	No	4.98	1.14				
N10-4/33	Bone	18.7	**2.73**	**0.41**	No	4.82	1.01	**-8.0**	**6.9**	**3.22**	9.35
	M1	17.9	2.81	0.3	No	4.82	1.40				
N10-4/42	Bone	**16.5**	2.99	0.43	No	**4.93**	**1.25**				
	M1	19.4	2.72	0.33	No	4.87	1.47				
N10-4/44	Bone	16.7	2.93	0.39	No	4.93	1.17	-8.8	8.5	3.23	6.17
N10-4/45	Bone	19.4	3.07	0.33	No	4.99	0.81				
	M1	**19.8**	2.49	0.39	No	**4.88**	**1.36**				
N10-7/1	Bone	17.4	3.01	0.37	No	5.41	1.23	-8.1	9.3	3.16	4.35
	M1	19.2	2.69	0.34	No	4.95	1.56				
N10-9/1	Bone	17.7	**2.80**	**0.51**	No	5.13	1.08				
	di	18.8	2.50	0.48	No	4.76	1.46				
N10-9/10	Bone	17.5	2.71	0.51	No	5.00	1.09				
	M1	18.0	**2.81**	**0.34**	No	5.10	1.70				
N10-9/2	Bone	**16.7**	2.94	0.38	No	**4.87**	**1.26**				
	dm1	19.4	2.73	0.33	No	4.85	1.46				
N10-9/6	Bone	**17.4**	2.85	0.46	No	**5.09**	**1.32**				
	dm1	18.8	2.59	0.39	No	4.83	1.55				
N11-5/7A	Bone	**16.7**	2.91	0.39	No	**5.02**	**1.38**				
	M1	19.4	2.59	0.41	No	4.87	1.58				
N11-5/7B	Bone	16.7	**3.01**	**0.37**	No	5.03	1.48				
	M1	**19.2**	2.67	0.35	No	**4.92**	**1.63**				
N12-11/4 A	Bone	**17.1**	3.03	0.39	No	**5.06**	**1.34**				
	M1	18.6	2.55	0.49	No	4.84	1.56				
N12-11/5 A	Bone	17.8	2.83	0.33	No	5.31	1.39				

*This sample's bone $\delta^{18}O_p$ value was analyzed before it was determined the collagen yield was <1%.

Note: Values in boldface font represent averages.

[a] None of these $\delta^{18}O_p$ values currently have the breastfeeding adjustments applied.

[b] This column indicates whether a peak was present at 710 cm^{-1} (calcite) or 1096 cm^{-1} (francolite/fluorapatite) on the FTIR spectrum at 1 ‰ sensitivity using the OPUS NT peak-pick function.

[c] μmol/mg Ag_3PO_4

[d] mg produced/mg sample

Individual	Element	$\delta^{18}O_p$ /‰[a]	CI	C/P	FTIR peak?[b]	CO_2 Yield[c]	Ag_3PO_4 Yield[d]	$\delta^{13}C$ /‰	$\delta^{15}N$ /‰	C:N	Collagen % Yield[d]
	M1	18.2	2.84	0.32	No	4.86	1.47				
N12-11/GP 19	Bone	18.6	2.76	0.41	No	4.87	1.30	**-8.9**	**8.9**	**3.10**	8.73
	M1	**17.8**	2.42	0.48	No	**5.04**	**1.60**				
YDL I - 85 - 11	Bone	18.6	2.94	0.39	No	4.80	1.13	-8.7	12.7	3.21	8.07
	dc	19.7	2.90	0.29	No	5.03	1.56				
YDL I - 85- 17	Bone	17.0	**2.87**	**0.39**	No	4.93	1.23	-10.0	9.7	3.18	5.84
	M1	**19.3**	2.69	0.33	No	**4.94**	**1.61**				
YDL I - 85 - 1a	Bone	17.8	2.80	0.39	No	4.78	1.17	-8.7	9.4	3.23	4.79
	M1	17.6	3.04	0.26	No	4.97	1.65				
YDL I - 85 - 23	Bone	**17.3**	2.95	0.39	No	**5.00**	**1.24**	-8.6	10.0	3.12	8.66
	M1	18.2	2.96	0.28	No	4.90	1.46				
YDL I - 85 - 25	Bone	**17.7**	2.78	0.37	No	**5.03**	**1.38**				
	M1	18.4	2.45	0.49	No	4.93	1.56				
YDL I - 85 - 27	Bone	17.3	2.90	0.44	No	4.93	1.12	**-9.1**	**9.3**	**3.16**	**11.05**
	M2	19.7	2.99	0.27	No	4.81	1.55				
YDL I - 85 - 29	Bone	**17.1**	2.83	0.41	No	**4.98**	**1.16**	-9.2	10.0	3.11	5.48
YDL I - 85 - 3	Bone	17.6	2.93	0.43	No	4.83	1.06	**-8.6**	**10.6**	**3.17**	8.12
	M1	19.0	2.61	0.37	No	4.92	1.61				
YDL I - 85 - 37	Bone	17.9	2.87	0.42	No	4.80	1.13	-9.2	11.5	3.16	5.07
	dm1	19.6	2.74	0.37	No	4.89	1.38				
YDL I - 85 - 6	Bone	16.9	3.04	0.38	No	5.04	1.21	-9.3	10.1	3.17	5.87
	M1	18.9	2.86	0.28	No	4.92	1.46				
YDL I - 85 - 62	Bone	17.5	2.84	0.47	No	4.93	1.14	**-9.5**	**9.9**	**3.11**	**13.26**
	M1	17.9	**2.76**	**0.36**	No	4.93	1.33				
YDL I - 85 - 64	Bone	**17.7**	2.74	0.42	No	**5.03**	**1.21**				
	M1	20.3	2.77	0.33	No	4.89	1.65				
YDL I - 85 - 66	Bone	17.0	2.92	0.4	No	4.88	1.12	-9.2	9.5	3.16	5.39
	M1	**19.3**	2.92	0.25	No	**4.80**	**1.53**				
YDL I - 85 - 70	Bone	18.0	3.05	0.41	No	4.83	1.22	**-9.2**	**10.0**	**3.13**	**12.15**
	M1	18.3	2.85	0.31	No	4.88	1.37				
YDL I - 85 - 73	Bone	17.8	2.98	0.38	No	4.83	1.37				
	M1	19.4	**2.58**	**0.46**	No	4.99	1.53				
YDL I - 85 - 74	Bone	**17.9**	2.91	0.45	No	**4.70**	**1.13**	-9.2	9.8	3.12	**6.04**
	M1	18.8	2.66	0.39	No	4.87	1.43				
YDL I - 85 - 81	Bone	16.9	2.85	0.41	No	5.08	1.32				
	M1	20.7	2.76	0.34	No	4.88	1.40				
YDL I - 85 - 82 b	Bone	17.2	3.00	0.42	No	4.92	1.11	-8.7	11.2	3.13	7.61
YDL I - 85 - 83	Bone	16.5	2.87	0.42	No	5.07	1.28	-9.7	9.8	3.21	4.75
	PM	18.3	2.70	0.34	No	4.86	1.56				
YDL I - 85 - 85	Bone	**16.7**	3.02	0.37	No	**4.96**	**1.09**	-8.4	9.5	3.13	5.61
YDL I - 85 - 86	Bone	**17.0**	2.94	0.37	No	**4.95**	**1.21**	-8.2	8.9	3.17	**6.12**
	M1	18.3	2.81	0.27	No	4.91	1.57				
YDL I - 85 - 89	Bone	16.6	2.83	0.43	No	4.91	1.13	**-9.3**	**8.9**	**3.15**	6.44

Note: Values in boldface font represent averages.
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[b] This column indicates whether a peak was present at 710 cm^{-1} (calcite) or 1096 cm^{-1}
(francolite/fluorapatite) on the FTIR spectrum at 1 ‰ sensitivity using the OPUS NT peak-pick function.
[c] μmol/mg Ag_3PO_4
[d] mg produced/mg sample

Individual	Element	$\delta^{18}O_p$ /‰[a]	CI	C/P	FTIR peak?[b]	CO_2 Yield[c]	Ag_3PO_4 Yield[d]	$\delta^{13}C$ /‰	$\delta^{15}N$ /‰	C:N	Collagen % Yield[d]
	M1	17.9	2.73	0.33	No	5.02	1.64				
YDL I - 85 - 97	Bone	**17.2**	**2.85**	**0.40**	No	**5.08**	**1.20**	-8.1	8.6	3.20	3.54
	M1	19.2	3.01	0.24	No	4.84	1.61				
YDL I - 85 - 99	Bone	17.7	2.88	0.47	No	4.80	1.18	**-8.4**	**9.7**	**3.14**	7.52
	M1	20.2	2.65	0.34	No	4.90	1.08				

Note: Values in boldface font represent averages.

[a] None of these $\delta^{18}O_p$ values currently have the breastfeeding adjustments applied.

[b] This column indicates whether a peak was present at 710 cm^{-1} (calcite) or 1096 cm^{-1} (francolite/fluorapatite) on the FTIR spectrum at 1 ‰ sensitivity using the OPUS NT peak-pick function.

[c] μmol/mg Ag_3PO_4

[d] mg produced/mg sample

Curriculum Vitae

Name: Alicia E. Donis

Post-secondary Education and Degrees:

2007 – 2013   M.A. Anthropology
                       The University of Western Ontario

2003 – 2007   B.A. Honours Anthropology
                       McMaster University

Honours and Awards:

2009   Social Science and Humanities Research Council (SSHRC)
                       Doctoral Fellowship
2008   Ontario Graduate Scholarship
2007 – 2012   Western Graduate Research Scholarship
2007   Canadian Graduate Scholarship: Master's Scholarship (SSHRC)
2007   The Richard Slobodin Prize – McMaster University
2007   The Leone Betty Blackwell Memorial Book Prize – McMaster
                       University
2006   The Dr. Harry Lyman Hooker Scholarship – McMaster University
2004, 2005, & 2006   Dean's Honour List – McMaster University
2004, 2005   The University (Senate) Scholarship – McMaster University

Related Work Experience:

2011 – 2012   Teaching Assistant, Department of Anthropology
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Publications and Conference Presentations:

Donis, Alicia E., Christine D. White, Linda Howie, Elizabeth Graham, and Fred J.
        Longstaffe
        2011 Diving into the Afterlife: Exploring a Distinct Burial Position at Postclassic
        Lamanai. Paper Presented at the Symposium on Current Research in Maya
        Bioarchaeology during the 76th Meeting of the Society for American
        Archaeology, Sacramento, California.

Donis, Alicia E.
        2007 Cough Won't Go Away? Medical Diagnosis and Treatment of
        Tuberculosis. *In* Before 'The San' : Tuberculosis in Hamilton at the Turn of the
        Twentieth Century. D. Ann Herring, ed. pp.83-92. Hamilton: Faculty of Social
        Sciences, McMaster University.