Prehispanic and Colonial Maya Subsistence and Migration: Contributions from Stable Sulfur Isotope Analysis

by © Asta Jade Rand

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Department of Archaeology
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ABSTRACT

The Maya who inhabited southeastern Mesoamerica from the Preclassic to Colonial periods (1000 BCE to 1821 CE) have been the focus of intensive archaeological study for over a century. Recent theoretical and methodological developments have contributed to nuanced understandings of Maya migration and subsistence practices. Stable sulfur isotope ($\delta^{34}S$) analysis of bone collagen is a novel technique that has been applied to Maya skeletal collections, although the variation in environmental $\delta^{34}S$ values throughout the Maya region has yet to be systematically characterized. This research presents the first Maya faunal sulfur isotope baseline based on the $\delta^{34}S$ values of 148 archaeological faunal remains from 13 sites in the Northern and Southern Lowlands. As expected, terrestrial animals in coastal areas had elevated $\delta^{34}S$ due to sea spray. However, those from inland sites had unexpectedly high $\delta^{34}S$ values that varied depending on the age of the underlying limestone. Although the $\delta^{34}S$ values of marine animals were lower than expected, similarly low values in freshwater animals permits the differentiation of freshwater and terrestrial animals at inland sites. These data demonstrate that sufficient variation in $\delta^{34}S$ values exists in the Maya region to identify sources of protein and nonlocal animals, which speaks to prehispanic Maya animal exchange and interregional interaction. The $\delta^{34}S$ values of 49 humans from seven Maya sites ranging from the Preclassic to Colonial periods were also interpreted using the faunal baseline. The spatial distribution of human $\delta^{34}S$ values differed from that of the terrestrial fauna, demonstrating sociocultural variation in Maya resource procurement in addition to underlying environmental influences. A comparison of carbon and nitrogen data from the same individuals also revealed the consumption of protein from different catchments. Nonlocal $\delta^{34}S$ values show three individuals migrated near the end of

their lives, and when integrated with childhood strontium and oxygen isotope data from tooth enamel, demonstrate a more robust means of investigating the length of residence and potentially the extent of integration into the receiving community. Finally, a case study of the prehispanic Maya from Nakum, Guatemala, demonstrates the contributions of stable sulfur isotope analysis to the interpretation of Maya subsistence strategies and migration when integrated into a multi-isotopic approach.

GENERAL SUMMARY

Although the Maya who lived in Central America from 1000 BCE to 1821 CE have been studied by archaeologists for over a century, new theories and methods have changed how archaeologists understand Maya migration and diet. Stable sulfur isotope values of animal and human bone come from the protein in their diet and show where they obtained their food. Researchers must therefore know the sulfur isotope values of plants and animals throughout a region to see if people consumed freshwater, marine, or terrestrial animals and if they moved to an area with different sulfur isotope values before they died. This method has been used in Maya archaeology, but the sulfur isotope values in this area are not well known.

This research analyzed sulfur isotopes in 148 archaeological animal bones from 13 sites to understand how they change throughout the Maya region. Marine and freshwater animals had lower values than terrestrial animals, allowing different types of protein in human diets to be identified. The terrestrial animal sulfur isotope values also relate to the age of limestone in an area, so that animals acquired nonlocally could be differentiated from local ones. The animal values provided a baseline for interpreting those of 49 human bones from seven inland Maya sites. Lower sulfur values from human tissues suggest the consumption of more freshwater animals. However, when interpreted with carbon and nitrogen isotope data, it seems the Maya ate plants and animals from different areas compared to the terrestrial animals. Three people also migrated to the sites where they were buried because their sulfur isotope values differed from the remaining individuals at each site. The length of time they lived where they were buried, and therefore their relationship with local people, was investigated by combining their sulfur isotope values with strontium

and oxygen isotope values from childhood, as well as archaeological data. A case study from the site of Nakum, Guatemala, shows how the analysis of sulfur isotopes and other data helps archaeologists understand what Maya people ate, if they moved, and how they lived in the past.

CO-AUTHORSHIP STATEMENT

Because this dissertation was written in a manuscript style, the chapters are in various stages of publication, several of which were written in collaboration with coauthors. The dissertation author was the primary author of the chapters presented within this dissertation, and is the primary author of all resulting publications, excluding that of the human sulfur isotope values from the Eastern Lowlands (see below for details). While the coauthors of Chapters 3 and 5 provided samples, resources, supervision, and comments on previous drafts, the dissertation author was responsible for the research design, sample acquisition and preparation, data interpretation, manuscript drafting and editing the chapters of this dissertation, submitting the resulting manuscripts for review, and incorporating reviewer and coauthor comments into subsequent drafts prior to publication. Details regarding the co-authors and publication venues for the data presented within this dissertation are provided below.

The author intends to submit Chapter 2 in the form of a review article to the *Journal of Archaeological Research* as the sole author. The faunal sulfur isotope baseline for the Maya region presented in Chapter 3 was coauthored with Dr. Carolyn Freiwald (University of Mississippi) and Dr. Vaughan Grimes (Memorial University of Newfoundland) and has been published in the *Journal of Archaeological Science: Reports* (Rand et al. 2021a).

While the dissertation author was the sole author of Chapter 4, the data presented therein will be distributed among several publication venues. For example, the human isotopic values from sites located in the Belize Valley and surrounding areas were included in a comprehensive analysis of sulfur isotopes from Maya remains in the Eastern Lowlands entitle “Paleodietary reconstruction and human mobility from the Preclassic through

Colonial periods in the Eastern Maya lowlands" currently under review by *PLoS One* (Manuscript #: PONE-D-21-05019) in collaboration with principle author Dr. Claire Ebert (University of Pittsburgh), as well as co-authors Dr. Kirsten Green-Mink (University of Montana), Dr. Julie Hoggarth (Baylor University), Dr. Freiwald, Dr. Jaime Awe (Northern Arizona University), Dr. Willa Trask (Defence POW/MIA Accounting Agency), Dr. Jason Yaeger (The University of Texas at San Antonio), Dr. M. Kathryn Brown (The University of Texas at San Antonio), Dr. Christophe Helmke (University of Copenhagen), Rafael Guerra (Institute of Archaeology, Belize), Dr. Marie Danforth (University of Southern Mississippi), and Dr. Douglas Kennett (University of California, Santa Barbara) (Ebert et al. under review).

The human isotopic data from Caledonia were also presented as a paper at the 48th Annual Meeting of the Canadian Association for Physical Anthropology in November 2020 co-authored with Dr. Freiwald and Dr. Grimes (Rand et al. 2020b). Similarly, the results from Xunantunich and San Lorenzo were presented at the first annual Bioarchaeology Early Career Conference (BECC) 2021 on March 25, 2021, with co-authors Dr. Freiwald, Dr. Yaeger, Dr. Brown, and Dr. Grimes (Rand et al. 2021b).

The human isotopic data from the Chac II and Calakmul have been submitted as reports to the Instituto Nacional de Antropología e Historia (INAH), and the author intends to publish those from Mission San Bernabé in Guatemala in collaboration with Dr. Freiwald, Dr. Katherine Miller Wolf (University of West Florida), and Dr. Timothy Pugh (City University of New York).

Finally, the isotopic case study from Nakum presented in Chapter 5 was published as a research article in the *Journal of Archaeological Science: Reports* (Rand et al. 2020a)

and was coauthored with Varinia Matute (Universidad de San Carlos de Guatemala), Dr. Grimes, Dr. Freiwald, Dr. Jarosław Źrałka (Uniwersytet Jagielloński), and Dr. Wiesław Koszkul (Uniwersytet Jagielloński). The Nakum data are also presented in a chapter in a monograph about the site and is currently in review (Rand and Freiwald n.d.).

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An endeavour such as this could not have been undertaken without the help, advice, and support of many people. I would first and foremost like to thank my supervisors, Dr. Vaughan Grimes (Memorial University of Newfoundland (MUN)) and Dr. Carolyn Freiwald (University of Mississippi). Dr. Grimes inspired me to investigate the application of sulfur isotope analysis in Maya archaeology and this project would never have come to fruition without the generosity of Dr. Freiwald. I am indebted to you both for your invaluable mentorship, support, training, and guidance throughout this process.

The Department of Archaeology, Memorial Applied Archaeological Sciences Laboratory, and School of Graduate Studies provided resources, assistance, and funding during my tenure at MUN, and I am grateful to the faculty and staff of each. I am particularly thankful for my supervisory and comprehensive exam committee members, Dr. Meghan Burchell (MUN), Dr. Michael Deal (MUN), Dr. Lisa Rankin (MUN), Dr. Kathryn Reese-Taylor (University of Calgary), and Dr. Peter Whitridge (MUN). I would also like to thank my defence examiners, Dr. Andrew Scherer (Brown University), Dr. Andrew Somerville (Iowa State University), and Dr. Whitridge, for your detailed comments on an earlier draft of this dissertation and stimulating questions during my defence. The thoughtful and constructive comments and advice from the members of my supervisory, comprehensive exam, and defence committees on earlier drafts of the chapters included in this dissertation has strengthened this research into a cohesive whole.

This work was also financially supported through several sources, including a Social Sciences and Humanities Research Council (SSHRC) of Canada Joseph-Armand Bombardier Canadian Graduate Scholarship (CGS) Doctoral Award (#767-2014-2712), as

well as a Scholarship in the Arts Doctoral Completion Award from the MUN Faculty of Social Sciences, a MUN Scotiabank Bursary for International Study, and a FA Aldrich Fellowship from the MUN School of Graduate Studies (SGS). Funding for the preparation and analysis of the Nakum human and faunal remains was provided to Dr. Jarosław Źrałka (Jagiellonian University) by the National Science Centre, Poland (under the agreement no. UMO-2014/14/E/HS3/00534).

This research would also not have been possible without the collaboration of numerous researchers who kindly provided samples for analyses. Dr. Paul Healy and Kate Dougherty of the Department of Anthropology at Trent University provided the human and faunal samples from Caledonia, Pacbitun, and Moho Cay, Belize. I am thankful to Dr. Healy for allowing me to continue my work with the Caledonia collection and for the opportunity to visit Trent again. Dr. Marilyn Masson (State University of New York at Albany) provided faunal samples from Caye Coco, Caye Muerto, Chanlacan, and the Laguna de On Island and Shore settlements. The human and faunal remains from Xunantunich and San Lorenzo in Belize were provided by Dr. Jason Yaeger (The University of Texas at San Antonio) and Dr. M. Kathryn Brown (The University of Texas at San Antonio), and the faunal remains from Caracol, Belize, were provided by Dr. Jaime Awe (Northern Arizona University). Dr. Źrałka provided the human and faunal samples from Nakum, Guatemala and generously provided lodging while I stayed in Flores analyzing the Nakum faunal collection. The human samples from Mission San Bernabé and faunal specimens from Tayasal, Guatemala, were provided by Dr. Timothy Pugh (City University of New York) and Evelyn Chan Nieto (Centro Universitario de Petén). The faunal remains from Oxtankah, San Miguelito, and Ichpaatun in Mexico were provided by

Dr. Allan Ortega Muñoz (Instituto Nacional de Antropología e Historia (INAH) of Mexico), and Dr. Jeffery Glover (Georgia State University) provided the faunal samples from Vista Alegre, Mexico. Finally, the human samples from Calakmul and Chac in Mexico were provided by Dr. Vera Tiesler (Universidad Autónoma de Yucatán) and Dr. T. Douglas Price (University of Wisconsin-Madison). I would also like to thank the Belize Institute of Archaeology (IOA), the Guatemalan Instituto de Antropología e Historia (IDAEH), and INAH for granting permission for the export and subsequent analyses of the samples included in this research, and Dr. Ortega Muñoz whose guidance and assistance in obtaining permission from INAH was indispensable.

The data presented in this dissertation was analyzed by several laboratories and I would like to extend my thanks to each. I am indebted to Alison Pye (MUN CREAIT – TERRA Facility) for her help and patience as I weighed samples for analysis, and for our lovely coffee chats. I would also like to thank Hilary Keats and Geert Van Bisen (MUN CREAIT – TERRA Facility) as well as Rebecca Lam (MUN CREAIT – MAF Facility) and Rachelle Brydon (MUN Archaeology Department) for their assistance with sample analysis at MUN. Unfortunately, all good things must come to an end and the TERRA Facility's MAT 252 mass spectrometer was sadly retired early in my tenure at MUN. Fortunately, Anthony Faiia (Department of Earth and Planetary Sciences Stable Isotope Laboratory, University of Tennessee Knoxville) and Paul Middlestead (Ján Veizer Stable Isotope Laboratory, University of Ottawa) agreed to analyze the stable sulfur isotopes of the remaining samples included in this dissertation, and I am indeed grateful for their collaboration.

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The results of this dissertation research have been and will be published in peer-reviewed venues, and I would like to thank my coauthors here. Dr. Freiwald and Dr. Grimes have been infinitely patient while commenting on various article drafts, and I thank them for their insightful suggestions and for their confidence in my work. I would also like to thank the coauthors of the Nakum publication (Rand et al. 2020a), Dr. Źrałka, Varinia Matute (Universidad de San Carlos de Guatemala), and Dr. Wiesław Koszkul (Jagiellonian University) for their assistance with funding, resources, samples, and analyses, and for their helpful comments on previous drafts of the manuscript. I would like to thank Dr. Ebert for the opportunity to include the Maya sulfur isotope data from several sites analyzed in this dissertation in a broader study of sulfur isotope variation across the Eastern Lowlands, along with coauthors, Dr. Kirsten Green-Mink (University of Montana), Dr. Julie Hoggarth (Baylor University), Dr. Freiwald, Dr. Jaime Awe (Northern Arizona University), Dr. Willa

Trask (Defence POW/MIA Accounting Agency), Dr. Christophe Helmke (University of Copenhagen), Rafael Guerra (Institute of Archaeology, Belize), Dr. Marie Danforth (University of Southern Mississippi), Dr. Jason Yaeger (The University of Texas at San Antonio), Dr. M. Kathryn Brown (The University of Texas at San Antonio), and Dr. Douglas Kennett (University of California, Santa Barbara). I would also like to thank Dr. Freiwald, Dr. Grimes, Dr. Yaeger, and Dr. Brown for agreeing to coauthor and making insightful comments and suggestions on papers presented at the annual meeting of the Canadian Association for Physical Anthropology (CAPA 2020) and Bioarchaeology Early Career Conference (BECC 2021).

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LIST OF CONTRIBUTIONS

Peer Reviewed Journal Articles

2021 Rand AJ, Freiwald C, Grimes V. A multi-isotopic (δ^{13}C, δ^{15}N, and δ^{34}S) faunal baseline for Maya subsistence and migration studies. *Journal of Archaeological Science Reports* 37:102977. doi: 10.1016/j.jasrep.2021.102977.

2020 Freiwald C, Miller Wolf KA, Pugh T, Rand A, Fullagar P. Early colonialism and population movement at the Mission of San Bernabé, Guatemala. *Ancient Mesoamerica*. 31(3):543-553. doi: 10.1017/S0956536120000218.

2020 Rand AJ, Matute V, Grimes V, Freiwald C, Źrałka J, Koszkul W. Prehispanic Maya diet and Mobility at Nakum, Guatemala: A multi-isotopic approach. *Journal of Archaeological Science: Reports* 32C: 102374. doi: 10.1016/j.jasrep.2020.102374.

2015 Rand A, Bower M, Munkittrick J, Harris A, Burchell M, Grimes V. Comparison of three bone collagen extraction procedures: The effect of preservation on δ^{13}C and δ^{15}N values. *North Atlantic Archaeology* 4:93-113.

2015 Rand AJ, Healy PF, Awe JJ. Stable Isotopic Evidence of Ancient Maya Diet at Caledonia, Cayo District, Belize. *The International Journal of Osteoarchaeology* 25:401-413. doi: 10.1002/oa.2308.

In review Ebert C, Rand A, Green-Mink K, Hoggarth J, Freiwald C, Awe J, Trask W, J Yaeger, MK Brown, Helmke C, Guerra R, Danforth M, Kennett D. Applying sulfur isotopes to paleodietary reconstruction and human mobility from the Preclassic through Colonial periods in the Eastern Maya lowlands. *PLoS ONE*. Manuscript #: PONE-S-21-05019.

Sections in Edited Volumes

2018 Rand AJ, Nehlich O. Diet and sulfur isotopes. In: López-Varela S, editor. *The Encyclopedia of Archaeological Sciences*. Wiley-Blackwell. doi: 10.1002/9781119188230.saseas0186.

2017 Rand AJ. Ancient Maya mobility at Caledonia, Cayo District, Belize: Evidence from stable oxygen isotopes. In: Patton, M., Manion J., editors. *Trading Spaces: The Archaeology of Interaction, Migration and Exchange*. Proceedings of the 46th Annual Chacmool Conference. Calgary, AB: Chacmool Archaeology Association, the University of Calgary. p. 32-43.

Accepted Freiwald C, Rand A, Belanich J. What's new in molecular approaches to bones, inside and out. In Tiesler V, editor. *Handbook of Mesoamerican Bioarchaeology*. Routledge. To be published in 2021.

In review Rand A, Freiwald C. Reconstructing the isotopic life histories of the Nakum Maya. In *The Nakum Archaeological Project Monograph Series*, edited by J Źrałka. Cracow: Jagiellonian University Press. To be published in 2021.

Conference Abstracts

2017 Rand A, Grimes V. The environmental sulfur isotope composition of the Maya Region: A working model and preliminary results. *American Journal of Physical Anthropology* 162(S64):327. doi: 10.1002/ajpa.23210

Presented Papers

2021 Rand AJ, Freiwald C, Yaeger J, Brown MK, Grimes V. Interpreting Maya migration from birth to death: A multi-isotopic case study from Xunantunich and San Lorenzo, Belize. Paper presented synchronically at the Bioarchaeology Early Career Conference (BECC) 2021, March 25-28.

2020 Rand AJ, Freiwald C, Grimes V. *Ancient Maya Catchment Use: Stable Sulfur Isotopic Evidence from Caledonia, Cay District, Belize*. Paper presented synchronically at the 48th Annual Meeting of the Canadian Association for Physical Anthropology, November 4-6.

2018 Freiwald C, Green K, Rand A, Trask W, Novotny A. *Maya Mobility: Isotopes, Molecules and Migration in Belize*. Paper presented at the 16th Annual Belize Archaeology Symposium, San Ignacio, Belize, June 27-29.

2015 Bower M, Rand A. *Contemplating the Relationship between Mobility Theory and Bioarchaeology: Past and Present Behaviours*. Paper presented at the 47th Annual Meeting of the Canadian Archaeological Association, Memorial University of Newfoundland, St. John's, NL, April 29 – May 3.

2013 Rand A. *Characterizing Human Mobility at Caledonia, Cayo District, Belize: Evidence from Stable Oxygen Isotope Analysis*. Paper presented at the 46th Annual Chacmool Archaeology Conference, University of Calgary, Calgary, AB, November 7-9.

2011 Rand A. *Isotopic Investigations of Diet at Caledonia, Cayo District, Belize*. Paper presented at the 39th annual meeting of the Canadian Association for Physical Anthropology, Montreal, QC, October 26-29.

Presented Posters

2017 Rand A, Grimes V. *The Environmental Sulfur Isotope Composition of the Maya Region: A Working Model and Preliminary Results*. Poster presented at the 86th annual meeting of the American Association of Physical Anthropologists, New Orleans, LA, April 20.

2014 Rand A, Munkittrick J, Harris A, Bower M, Burchell M, Grimes V. *Comparing Three Collagen Extraction Procedures for Stable Carbon and Nitrogen Isotope Analysis of Archaeological and Modern Bone*. Poster presented at the 42nd annual meeting of the Canadian Association for Physical Anthropology, Fredericton, NB, November 6-9.

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CHAPTER 1

INTRODUCTION

Evidence of human migration and subsistence practices in past cultures are of archaeological interest as these data provide insight into broader cultural processes such as social differentiation, economics, trade, and politics (Anthony 1990; Cameron 2013; Hastorf 2017; Sharpe and Emery 2015; White 2005; White et al. 2006; Wright et al. 2010). The investigation of these topics has benefited from the isotopic analysis of archaeological human and faunal remains because they can directly assess the types of foods consumed and whether individuals were born near the site where they were buried. Among the prehispanic and Colonial period Maya[1] who lived in northwestern Central America, stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope analyses have revealed the amount of maize (corn) and animal protein in the diet (Somerville et al. 2013; Tykot 2002; White and Schwarcz 1989), and radiogenic strontium ($^{87}Sr/^{86}Sr$) and stable oxygen ($\delta^{18}O$) isotope analyses have successfully identified nonlocal humans and animals at Maya sites (Freiwald and Pugh 2018; Freiwald et al. 2014; Price et al. 2008, 2014; Scherer et al. 2015; Thornton 2011; Wright 2012).

[1] The term "Mayan" refers to the language spoken by Maya people, whereas "Maya" is used to refer to all other aspects of these people and their culture, past and present (Sharer and Traxler 2006:23).

The analysis of stable sulfur isotope ($\delta^{34}S$) values from human and animal bone collagen offers a complementary isotopic technique that differentiates between the consumption of terrestrial, freshwater, and marine protein, and identifies nonlocal individuals in archaeological contexts (Nehlich 2015). Stable sulfur isotope analysis has recently revealed subsistence practices and residency at the Maya sites of Cahal Pech (n = 5; Awe et al. 2017; Green 2016) and Caledonia (n = 14; Rand and Grimes 2017). However, these studies are limited to the analysis of small human skeletal collections (n < 15) from two sites in western Belize that primarily date to the Classic period. Thus, the objective of this doctoral research is to expand upon these preliminary studies and establish the utility of stable sulfur isotope analysis for contributing to archaeological interpretations of prehispanic and Colonial period Maya subsistence strategies and migration.

1.1 A Brief Introduction to the Maya

Archaeologically, the Mesoamerican culture region includes southern Mexico, the Yucatan Peninsula, Guatemala, El Salvador, and parts of Honduras (Joyce 2003). As illustrated in Figure 1.1, the subregion inhabited by the prehispanic and Colonial Maya encompasses the modern countries of Belize and Guatemala, as well as southeastern Mexico, western Honduras, and El Salvador (Sharer and Traxler 2006:26). The Maya region may be further divided into six geocultural areas: The Northern Lowlands, the Southern Lowlands, the Maya Mountains, the Motagua River Valley, the Highlands, and the Pacific Coast (Hodell et al. 2004; Sharer and Traxler 2006:29-53).

While the Maya region was characterized by common sociocultural features, such as related languages, iconography, ideology, architectural styles, and settlement patterns,

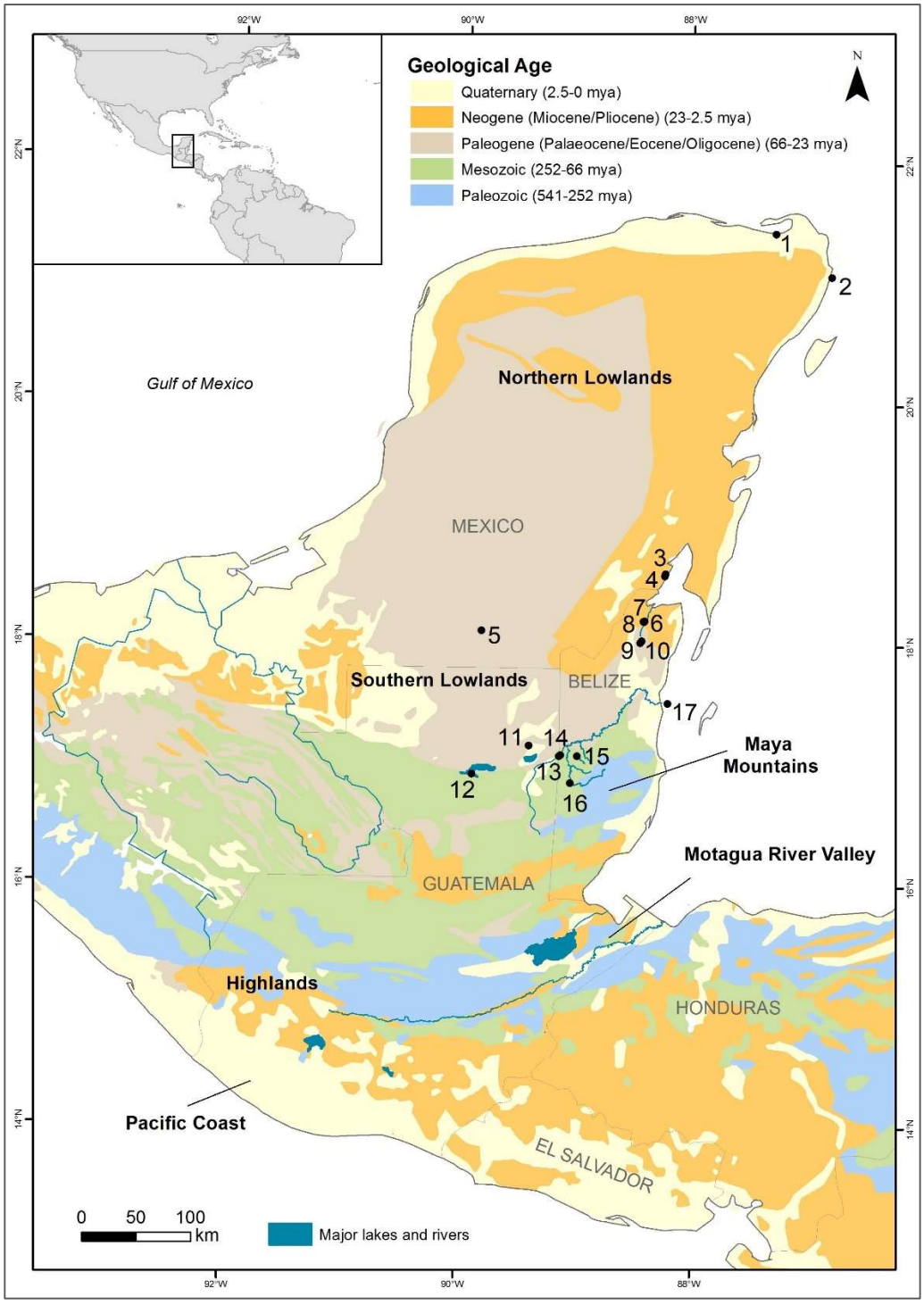

Figure 1.1: Map of the Maya region identifying the Northern Lowlands, the Southern Lowlands, the Maya Mountains, Highlands, Pacific Coast, and Motagua River Valley. Sites include (1) Vista Alegre, (2) San Miguelito, (3) Oxtankah, (4) Ichpaatun, (5) Calakmul, (6) Caye Muerto, (7) Chanlacan, (8) Caye Coco, (9) Laguna de On Island, (10) Laguna de On Shore, (11) Nakum, (12) Mission San Bernabé, (13) Xunantunich, (14) San Lorenzo, (15) Pacbitun, (16) Caledonia, and (17) Moho Cay. Map created by Bryn Trapper based on the Geological Map of North America 2005 (1:5,000,000) (Garrity and Soller 2009).

the prehispanic Maya comprised a complex mosaic of communities that varied in terms of political organization, economy, social structure, subsistence, and interactions over both space and time (Sharer and Traxler 2006:93). Although occupied since the Palaeoindian period, the first evidence of sedentary agricultural communities in the Maya region occurred during the Archaic period (see Table 1.1). The subsequent Preclassic period was characterized by the growth of settled communities, the cultivation of staple crops including maize (corn), beans, squash, and chilies, as well as the development of pottery and more complex societies (Sharer and Traxler 2006:155). Social organization was kin-based, but social stratification and kingship developed during this period (McAnany 1995). The first Maya cities, including Uaxactun, Nakbe, and El Mirador (Clark et al. 2000) were

Table 1.1: Chronological periods in Maya archaeology.

Period	Date Range
Colonial	1697 - 1821 CE
Contact	1525 - 1697 CE
Postclassic	900/1100 - 1525 CE
Late Postclassic	1300 - 1525 CE
Early Postclassic	900/1100 - 1300 CE
Classic	250 - 900/1100 CE
Terminal Classic	800 - 900/1100 CE
Late Classic	600 - 800 CE
Early Classic	250 - 600 CE
Preclassic	2000 BCE - 250 CE
Terminal Preclassic*	100 - 250 CE
Late Preclassic	400 BCE - 100 CE
Middle Preclassic	1000 - 400 BCE
Early Preclassic	2000 - 1000 BCE
Archaic	8000 - 2000 BCE
Paleoindian/Lithic	12,000/20,000 - 8000 BCE

Note: Period names and date ranges from Sharer and Traxler (2006:98). The Postclassic was subdivided into Early and Late periods after Masson (1993), and the Contact and Colonial date ranges are based on sites in the Peten lakes region of Guatemala (after Pugh et al. 2016:51), where colonialism was resisted until much later than elsewhere in Mesoamerica (Jones 1998; Schwartz 1990).
*Also called the Protoclassic period (see Źrałka et al. 2018).

established around 750 BCE, and by 500 BCE they were characterized by monumental architecture such as large temples covered with stucco façades. Material culture also evidences a high degree of interregional interaction during the Middle Preclassic period (Rice 2015). This was followed by the development of hieroglyphic writing by the 3rd century BCE and the establishment of divine kingship and the proliferation of large centres in Peten, Guatemala, in the lowlands (McKillop 2004:8; Sharer and Traxler 2006:155).

The florescence of the Maya civilization in Peten during the Classic period was defined by the expansion of the social processes that originated during the Preclassic period and the appearance of stone sculptures (stelae) with Long Count dates. While kinship continued to serve as the primary means of social organization, social stratification and kingship that appeared during the Late and Terminal Preclassic periods grew increasingly important during the Classic period (McAnany 1995; Reese-Taylor and Walker 2002). Classic period rule was based on the concept of divine kingship, where rulers acted as mediators between the Maya people and the supernatural. During this period, the Maya were organized into highly stratified, competitive city-states, comprised of a city surrounded by supporting hinterland communities, such as at Caracol, Lamanai, Kaminaljuyu, Copan, Tikal, and Calakmul (Martin and Grube 2008). These city-states had complex relationships involving allegiances, rivalries, warfare, and trade arrangements that waxed and waned over the Classic period (Chase and Chase 1998; Martin and Grube 2008).

The elite members of these societies were wealthy, as evidenced by the goods included in their mortuary contexts (Fitzsimmons 2009), and likely exercised control over many aspects of Maya life. Building on developments during the Preclassic period, Classic period Maya participated in far reaching Mesoamerican trade networks, exchanging both

exotic (i.e., obsidian, green stone, etc.) and mundane (i.e., salt, grinding stones) goods (see Masson and Freidel 2002; Sharer and Traxler 2006:660-664). They also believed in a multifaceted religion, involving ancestor veneration, human and auto-sacrifice, and participation in elaborate rituals (Fitzsimmons 2009; McAnany 1995; Sharer and Traxler 2006:719-756). It is this period that has defined the traditional representation of prehispanic Maya culture. However, during the Terminal Classic period, Classic Maya society began to decline in the Southern Lowlands due to various complex and often debated causes (e.g., Iannone et al. 2016; Kennett et al. 2012; Wright and White 1996), leading to the abandonment of the large Classic period centres in what has been uncritically termed the "collapse" of Maya civilization (Demarest 2004:242).

The discontinuance of Classic period hallmarks, including divine kingship and Long Count dates, caused researchers to initially view the Postclassic period as one of decline and impoverishment (Demarest 2004:277). However, the Maya continued to thrive in the Northern Lowlands and Highlands, as well as at certain sites in the Southern Lowlands during the Postclassic period (McKillop 2004:14). The Maya states that arose during this period were based on more flexible political and economic institutions that replaced divine kingship (Demarest 2004:277). Local economies also became less self-sufficient and were more focused on the overproduction of commodities for trade. Warfare and tribute continued to be important but involved longstanding feuds among lineages rather than the prestige of a single ruler (Demarest 2004:278).

In the sixteenth century, the Spanish first made contact with Maya populations. The impact of this was initially indirect, including the introduction of new diseases such as smallpox, which devastated Maya populations and destabilized political systems (Lovell

1992). Subsequent attempts by the Spaniards to conquer the Maya were met with resistance that was much more effective than in other areas of Mesoamerica (Jones 1998). Eventually, Maya resistance to colonial rule was overcome, and they were assimilated into Spanish colonial culture (Jones 1998; Schwartz 1990). Despite the horrific impact of conquest and domination on the Colonial period Maya, their traditions continued to evolve and thrive through their descendants who live in the region today (Demarest 2004:286-289).

The prehispanic Maya have been the centre of archaeological study for well over a century (Demarest 2004; Evans 2004; McKillop 2004; Sharer and Traxler 2006). Studies of material culture (i.e., artifacts, architecture, epigraphy, iconography, etc.) and human osteology have greatly contributed to current understandings of prehispanic Maya life. For example, prehispanic Maya subsistence practices are evidenced by the recovery of botanical and faunal remains from archaeological sites, assessment of pathological conditions on human skeletons, artifact analysis, linguistic studies, and analogy (Götz and Emery 2013; Staller and Carrasco 2010; White 1999). Similarly, the movement of individuals throughout the Maya region has been reconstructed using the appearance of foreign artifacts and architecture, cranial and dental modification, and the distribution of sites, material culture, and genetic traits (Bove and Medrano Busto 2003; Braswell 2003; Cucina 2015a; Domínguez Carrasco and Folan Higgins 2015; Inomata 2004; Rice 2015; Smyth and Rogart 2004; Tiesler 2015).

The development of isotopic techniques over the last 30 years have also contributed to the reconstruction of prehispanic Maya subsistence practices and migration because they directly assess the types of foods individuals consumed as well as whether they relocated from an isotopically distinct area. Stable carbon and nitrogen isotope analysis have been

used to investigate the amount of maize and meat in Maya diets, and whether these proportions varied by age, sex, and social status, and across time and space (Tykot 2002; White 1999). The analysis of animal remains has also provided insights into domestication and animal management among the Maya (Thornton 2011; Sharpe et al. 2018). Isotopic studies further demonstrate that the prehispanic Maya traded faunal resources over long distances, although they were also experts at utilizing those present in the local environment (Götz 2008; Emery 2004a; Sharpe and Emery 2015; Thornton 2011; Whittington and Reed 1997a), and that the Maya themselves were more mobile than originally thought (Freiwald 2011a; Freiwald et al. 2014; Miller 2015; Miller Wolf and Freiwald 2018; Ortega-Muñoz et al. 2019; Price et al. 2014, 2018a, 2018b, 2019; Somerville et al. 2016; Suzuki et al. 2018, 2020; Wright 2005a, 2012). These studies have facilitated nuanced interpretations of Maya migration, including whether nonlocal individuals varied by age, sex, or social status. More detailed examinations of sociocultural processes, including economics and exchange, captive-taking, and political organization among the prehispanic Maya have also been investigated (Cucina 2015a; Price et al. 2008, 2010; Wright 2012; Wright et al. 2010; Freiwald et al. 2014). Overall, these studies provide an excellent framework within which the utility of stable sulfur isotope analysis in the Maya region may be evaluated.

1.2 Applications of Sulfur Isotope Analysis in Archaeology

Stable sulfur isotope analysis of human and faunal bone has recently emerged as a useful technique for addressing archaeological questions related to subsistence and migration (Nehlich 2015). The sulfur isotope values of human and animal bone collagen are derived from dietary protein (Brosnan and Brosnan 2006; Ingenbleek 2006), which in

turn is assimilated from inorganic sulfate from the environment into amino acids (methionine and cystine) by plants at the base of the food chain (Monaghan et al. 1999; Trust and Fry 1992). Environmental $\delta^{34}S$ values are primarily determined by the underlying geology (Krouse et al. 1991; Hitchon and Krouse 1972; Krouse and Levinson 1984), although biological processes such as the reduction and re-oxidation of sulfur by bacteria (Jørgensen et al. 2019) and atmospheric sulfate sources, such as sea spray in coastal areas (Coulson et al. 2005; McArdle et al. 1998; Wadleigh et al. 1994), can also influence environmental $\delta^{34}S$ values, and therefore those of plants and their consumers.

Although initially employed to study ecological relationships in various modern environments (Chukhrov et al. 1980; Fry et al 1982; Hobson 1999; Krouse and Grinenko 1991; Peterson and Fry 1987; Trust and Fry 1992), the potential of $\delta^{34}S$ values from bone collagen for reconstructing archaeological human diets was noted in the 1980s (DeNiro 1987:190; Krouse et al. 1987). The first studies to analyze $\delta^{34}S$ values from archaeological humans sampled hair (Aufderheide et al. 1994; Macko et al. 1999) because it has a higher concentration of sulfur than does bone and early methods required large samples for analysis (Leach et al. 1996; Udea and Krouse 1986). Subsequent analytical improvements (Giesemann et al. 1994) now allow for the analysis of much smaller samples of bone (≤15 mg), making this technique viable in archaeological research (Richards et al. 2001).

Over the past 20 years there has been a significant increase in the number of archaeological studies that have analyzed sulfur isotopes from bone collagen (Fig. 1.2), typically in conjunction with the analysis of other isotope systems, such as carbon, nitrogen, oxygen, and strontium. Initial studies applied stable sulfur isotope analysis of human and animal bone collagen to address archaeological questions related to marine, terrestrial, or

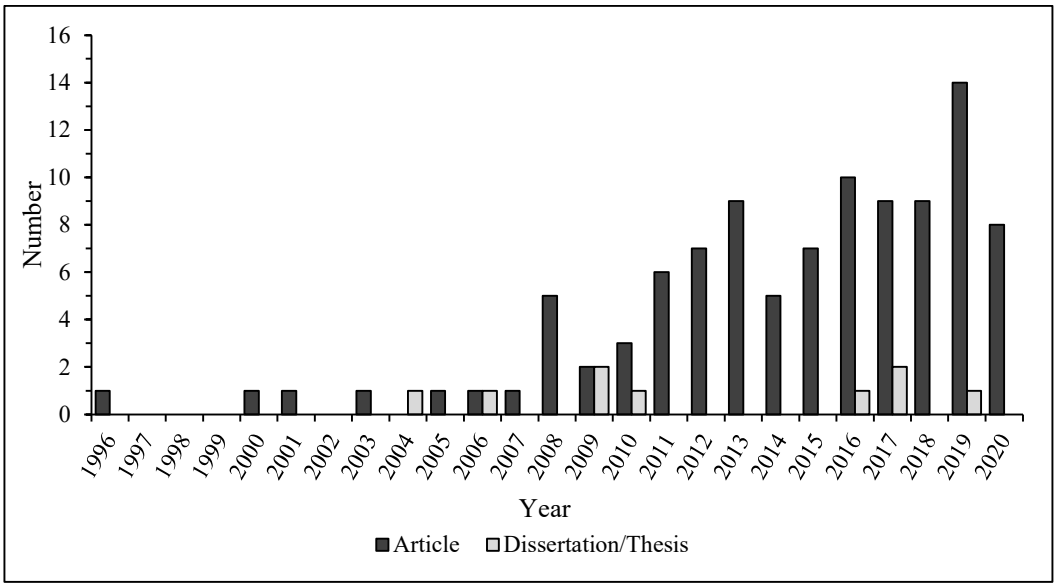

Figure 1.2: Number of archaeological studies that utilized stable sulfur isotope analysis of human and/or faunal bone collagen by year. Data collected through a Google Scholar™ search starting at the year 1996 using the key words "sulfur" or "sulfur" and "isotope" and "archaeology". Note that only peer-reviewed articles and graduate theses and dissertations were included, and that review articles, modern feeding studies, and studies that analyzed tissues other than bone collagen were omitted.

freshwater diets (Craig et al. 2006; Hu et al. 2009; Leach et al. 1996; Nehlich et al. 2010, 2011, 2012; Privat 2004; Privat et al. 2007; Richards et al. 2001; Sayle et al. 2013), gendered differences in protein consumption (Howcroft et al. 2012), weaning diets (Howcroft et al. 2012; Nehlich et al. 2011), and to identify human migration (Nehlich et al. 2012; Vika 2009). Other studies assessed methodological concerns associated with the application of stable sulfur isotope analysis for reconstructing subsistence practices and migration in archaeological contexts (Bocherens et al. 2011; Craig et al. 2006; Nehlich 2009; Nehlich and Richards 2009; Privat et al. 2007; Richards et al. 2001, 2003).

Stable sulfur isotope analysis of faunal remains has also contributed to understandings of the past. Such studies have used faunal $\delta^{34}S$ values to reconstruct paleoenvironments (Arppe et al. 2019; Britton 2010; Drucker et al. 2011, 2012, 2015,

2018a; Fuller et al. 2020; Jones et al. 2018; Swift et al. 2017), and to investigate animal husbandry (Fraser et al. 2017; Guiry et al. 2015; Towers et al. 2011) and management (Madgwick et al. 2013; Valenzuela et al. 2016), as well as the production and exchange of worked bone artifacts (Sayre et al. 2016) in archaeological societies. The analysis of faunal remains for establishing comparative bioavailable $\delta^{34}S$ baseline values (Bocherens et al. 2015; Nehlich et al. 2013; Sparks and Crowley 2018) is also necessary for the interpretation of human values.

Most research now incorporates sulfur isotope analysis of both human and faunal bone collagen into multi-isotopic investigations of diet and/or mobility in archaeological case studies (Fig. 1.3), particularly of sites in Europe (Athfield et al. 2008; Bollongino et al. 2013; Bollongino et al. 2013; Bonilla et al. 2019; Bonsall et al. 2015; Bownes et al.2017;

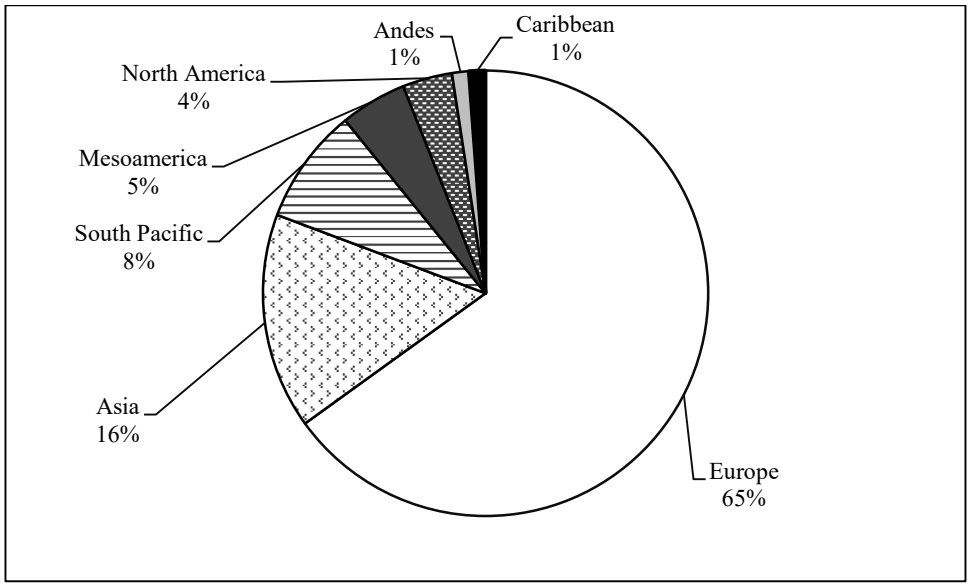

Figure 1.3: Percentage of case studies that analyzed $\delta^{34}S$ values from human and/or faunal bone collagen by region of research. Data collected through a Google Scholar™ search starting at the year 1996 using the key words "sulfur" or "sulfur" and "isotope" and "archaeology". Note that only case studies presented in peer-reviewed articles and graduate theses and dissertations were included, and that review articles, modern feeding studies, and studies that analyzed tissues other than bone collagen were omitted.

Colleter et al. 2019; Craig et al. 2010; Curto et al. 2019; Drucker et al. 2018a, 2020; Dury et al. 2018; Eriksson et al. 2013, 2018; Fornander 2013; Fornander et al. 2008; Goude et al. 2019, 2020a, 2020b; Hamilton et al. 2019; Hemer et al. 2017; Howcroft et al. 2012; Jay 2013; Jovanović et al. 2019; Lamb et al. 2012; Le Huray 2006; Lelli et al. 2012; Linderholm and Kjellström 2011; Linderholm et al. 2008a, 2008b, 2014; Lopez Aceves 2019; MacRoberts et al. 2020; Madgwick et al. 2019a, 2019b; Moghaddam et al. 2016, 2018; Nehlich et al. 2010, 2011, 2014; Oelze et al. 2012a, 2012b; Palomäki 2009; Parker Pearson et al. 2016; Rey et al. 2019; Richards et al. 2001, 2008; Smits et al. 2010; Sundman 2018; van der Sluis et al. 2016; Vika 2009). Other case studies focus on sites in China (Cheung et al. 2017a, 2017b; Guo et al. 2018; Hu et al. 2009; Ma et al. 2016), Japan (Tsutaya et al. 2016, 2019), Korea (Choy et al. 2015), Turkey (Caldeira 2017; Irvine and Erdal 2020; Irvine et al. 2019; Lösch et al. 2014), and Siberia (Svyatko et al. 2017), as well as in the south Pacific (Kinaston et al. 2013a, 2013b, 2014; Leach et al. 1996, 2000, 2003; Stantis et al. 2015), Iceland (Hamilton and Sayle 2019; Sayle et al. 2014, 2016; Walser et al. 2020), California (Eerkens et al. 2016), Canada (Bocherens et al. 2016; Diaz 2019), Peru (Gerdau-Radonićet al. 2015), and the Caribbean (Sparks and Crowley 2018). In addition to case studies, other research has recently integrated stable sulfur, carbon, and nitrogen isotope analysis into Bayesian mixing models to better understand individual diets and the influence of freshwater and marine resources on radiocarbon dates (Bocherens et al. 2016; Bownes et al. 2017; Dury et al. 2018; Hamilton and Sayle 2019; Petchey and Green 2005; Sayle et al. 2014).

Most of these studies have been conducted in temperate regions of the world, particularly in Europe (see Fig. 1.3). Few studies have applied sulfur isotope analysis in

tropical areas, all of which have analyzed skeletal collections from tropical islands that often exhibit elevated $\delta^{34}S$ values due to the influence of sea spray (Kinaston et al. 2013a, 2013b, 2014; Leach et al. 1996, 2000, 2003; Sparks and Crowley 2018; Stantis et al. 2015). The initial studies that have analyzed the stable sulfur isotopes of archaeological Maya skeletal collections (Awe et al. 2017; Green 2016; Rand and Grimes 2017; Rand et al. 2020a, 2020b; this study) represent the first application of this technique in an inland, continental, and tropical archaeological culture area. Building upon the findings of archaeological and modern sulfur isotope studies applied elsewhere in the world, as well as the pioneering studies in the Maya region, the goals of this doctoral research were to:

(1) Define the variation in $\delta^{34}S$ values among different environments in the Maya region by establishing a baseline from the values of archaeological fauna.

(2) Evaluate the faunal baseline through the analysis of stable sulfur isotopes from archaeological human remains from Maya sites.

(3) Demonstrate the contributions of stable sulfur isotope analysis for interpretations of Maya migration and subsistence practices through a comparison of the results with those of other isotopic assays, archaeological data, and ethnohistoric accounts.

This dissertation is written in a manuscript style so that individual chapters represent stand-alone manuscripts drafted for publication in peer-reviewed venues. However, each chapter addresses the goals of this doctoral research and thus contributes to the cohesiveness of the dissertation. The dissertation author was the principal author of all chapters and details regarding the publication venues and roles of coauthors can be found in the Co-Authorship Statement as well as in the footnotes provided at the beginning of each chapter.

1.3 Chapter Descriptions

Following this introduction, Chapter 2 describes how isotopic techniques have contributed to archaeological understandings of migration in past societies, including the Maya. The conceptualization of migration in both archaeology and bioarchaeology has been influenced not only by fluctuations in predominant disciplinary theoretical paradigms (Adams et al. 1978; Agarwal and Glencross 2011; Anthony 1990, 1992; Burmeister 2000; Washburn 1951; Zuckerman and Armelagos 2011) but also by the methods available for identifying migration in archaeological contexts (Hakenbeck 2008; Scharlotta et al. 2018). The ability to directly assess whether an individual moved to the place he or she was buried using isotopic techniques has led me to redefine *isotopically identifiable migration* in archaeological contexts as *the relocation of a sampled individual to an isotopically distinct environment at least once during his or her life* (Chapter 2:41). Stable isotope analyses are not only useful for reconstructing the migration histories of individuals, but also for understanding aspects of the process of migration in archaeological societies when the results are properly contextualized using multiple lines of evidence, as illustrated in a review of isotopically identified migration in the Maya region.

The extensive application of isotopic techniques in the Maya region, combined with the rich archaeological record from this culture area, permits a critical evaluation of the utility of stable sulfur isotope analysis for identifying Maya migration and subsistence strategies. The variation in biologically available (bioavailable) stable sulfur isotope values throughout the Maya region, however, must first be determined. Thus, Chapter 3 presents the stable sulfur, carbon, and nitrogen isotope values of 148 archaeological animal bone

samples from 13 Maya sites to assess the variability in environmentally bioavailable $\delta^{34}S$ values in the Maya region modelled by Rand and Grimes (2017). This also represents the first extensive faunal sulfur baseline for this culture area. As elsewhere in the world, terrestrial, freshwater, and marine animals exhibit different $\delta^{34}S$ values, although some unexpected variation was observed. While the $\delta^{34}S$ values of terrestrial animals from coastal sites were elevated due to sea spray sulfate as predicted, marine taxa had unexpectedly low $\delta^{34}S$ values, perhaps due to the consumption of plants that assimilated sulfur from sulfide produced from microbial dissimilatory sulfate reduction (DSR) or subsequently re-oxidized sulfate from anaerobic environments, or those influenced by freshwater with lower $\delta^{34}S$ values. In contrast, terrestrial animals from inland sites had much higher $\delta^{34}S$ values than expected due to the underlying limestone geology of much of the Yucatan Peninsula, although these values did vary based on the age of the underlying limestone. The lower $\delta^{34}S$ values of freshwater species are likely due to DSR in anerobic freshwater sediments, as well as differences in the $\delta^{34}S$ values deposited by various inputs along the course of rivers. When the data sets from each site were subdivided into terrestrial, freshwater, and marine species, the $\delta^{34}S$ values of nine fauna were identified as outliers. Although a freshwater turtle from Vista Alegre had a very low, DSR-influenced $\delta^{34}S$ value, eight terrestrial animals from six sites were nonlocal, providing insights into Maya exchange of faunal resources, and therefore interregional interaction. Importantly, the faunal data demonstrate there is sufficient variation in $\delta^{34}S$ values throughout the Maya region to investigate human subsistence practices and migration.

Using the baseline faunal sulfur data from Chapter 3, prehispanic and Colonial period Maya subsistence practices and migration were interpreted based on the $\delta^{34}S$ values

of 49 humans from seven Maya sites in Chapter 4. At two of the three sites for which human and fauna samples were analyzed, the human $\delta^{34}S$ values were lower, suggesting the consumption of freshwater fish or reliance on lime-processed maize irrigated with DSR-influenced water. The spatial distribution of human and faunal $\delta^{34}S$ values also differed, reflecting sociocultural variation in Maya use of multiple catchments with different environmental $\delta^{34}S$ values. For example, comparison of the $\delta^{34}S$ and $\delta^{13}C$ values at Caledonia revealed some Maya consumed maize-based protein from the limestone Vaca Plateau, whereas others were more reliant on animal protein from the Mountain Pine Ridge of the Maya Mountains or the Macal River, although it was not possible to identify this at other sites due to equifinality, whereby different areas or environments exhibit overlapping isotope values. The isotopic data also revealed temporal variation in subsistence practices, wherein the Colonial period individuals from Mission San Bernabé had elevated and homogenous $\delta^{34}S$, $\delta^{13}C$, and $\delta^{15}N$ values compared to the Maya of earlier periods, indicative of dietary change resulting from Colonialism. It was also possible to identify recent migrants to Xunantunich, Caledonia, and Pacbitun as individuals with statistically outlying $\delta^{34}S$ values. The comparison of the bone $\delta^{34}S$ values that reflect place of residence during adulthood with childhood residence indicated by tooth enamel $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values from the same individual, combined with contextual data, also provided insights into the length of time individuals lived at their place of burial and the degree to which nonlocal individuals were integrated into prehispanic Maya communities.

The utilization of an archaeologically contextualized multi-isotopic approach to understandings of Maya subsistence practices and migration is illustrated in a case study from Nakum, Guatemala, and presented in Chapter 5. Stable carbon, nitrogen, and sulfur

isotope analyses of 16 faunal specimens provided baseline values with which the values from five human bone collagen samples were compared. These data suggest the Nakum individuals consumed a typical Maya diet dependent on maize supplemented with other plants and animal protein. Although the faunal $\delta^{34}S$ values were higher than expected at an inland site due to the underlying limestone geology, one deer with an unusually low value was likely imported to the site from near the Maya Mountains. Additional carbon and oxygen isotope values from the bone apatite of the Nakum Maya, combined with the analysis of oxygen and strontium isotopes from the enamel of seven teeth from different contexts, also provided information on human migration to the site. Although the Nakum Maya exhibited local $^{87}Sr/^{86}Sr$ and $\delta^{34}S$ values, the very low $\delta^{18}O$ values from a deciduous tooth recovered from a context with Central Mexican aspects suggest this individual's mother moved to Nakum from beyond the Maya region. The nonlocal $\delta^{18}O$ value of a bone sample from a Terminal Classic termination deposit also provides insights into sociocultural interactions between local Nakum Maya and other areas during a turbulent period in the site's history, while circumventing equifinality in the $\delta^{34}S$ values. Overall, the case study demonstrates the strengths of an archaeologically contextualized multi-isotopic approach that analyzes fauna and multiple human tissues and integrates sulfur isotope data with those of more established isotopic techniques for the interpretation of Maya resource procurement and interregional interaction at Nakum.

Chapter 6 concludes the dissertation by summarizing the results and recommending areas for future research. Following the list of references cited within this dissertation, several appendices provide more detail on certain aspects of the research presented in the chapters. For example, because the same methodology was applied in Chapters 3, 4, and 5,

it is described in detail in Appendix A. Furthermore, the comparability of stable sulfur isotope values analyzed by different laboratories is considered in Appendix B. The analytical accuracy and precision of the isotopic data generated by each lab was calculated using the recommendations of Szpak and colleagues (2017a) and is presented in Appendix C. Finally, because of the large sample size included in this study, the contextual and isotopic data of the faunal samples are presented in Appendix D, and those for the human samples are presented in Appendix E.

CHAPTER 2

CONTRIBUTIONS OF ISOTOPIC ANALYSES TO CONCEPTUALIZATIONS OF MIGRATION IN MAYA (BIO)ARCHAEOLOGY[2]

Migration is an intrinsic aspect of human behaviour and is an important demographic and sociopolitical process in both modern and ancient societies (Baker and Tsuda 2015a; Brettell and Hollifield 2000a). However, the conceptualization of migration has a turbulent history in archaeological thought, related to paradigm shifts within the discipline (Adams et al. 1978; Cabana 2011; Chapman and Hamerow 1997a; Hakenbeck 2008; Peregrine et al. 2009; Section 2.1.1) that are paralleled in bioarchaeological theory (Agarwal and Glencross 2011; Armelagos and Van Gerven 2003; Hens and Godd 2008; Washburn 1951; Wood et al. 1992; Zuckerman and Armelagos 2011; Section 2.1.2). Much theoretical debate has centred on the traditional archaeological definition of "migration" as a rapid, unidirectional, and permanent relocation event involving a vast number of people, as well as the inability to identify migration in archaeological contexts (Burmeister 2000; Clark 1994; Hakenbeck 2008). Considerations of perspectives from related disciplines have helped to redefine migration in archaeological research (Anthony 1990; Cabana and Clark

[2] The author intends to publish the contents of this chapter as a review article to be submitted to the *Journal of Archaeological Research*.

2011a; Champion 1990; Kardulias and Hall 2007; Kristiansen 1989; Sjögren et al. 2016:3; Tsuda et al. 2015), as have advances in methods for identifying archaeological migration.

Although the archaeological study of human migration has long been informed by bioarchaeological data, methodological developments in genetics and biogeochemistry now provide direct evidence of human movement in the past and have substantially contributed to the revitalization of migration as a legitimate subject of study in archaeology (Hakenbeck 2008; Scharlotta et al. 2018). Isotopic analyses in particular have been viewed as a "way out" for archaeologists who have struggled to unequivocally prove human movement in the past (Hakenbeck 2008:19; Section 2.2). It is, however, necessary to recognize the inherent assumptions and limitations associated with these techniques to provide accurate interpretations of archaeological migration from isotopic data (Section 2.2.1). For example, although isotopic analyses identify migration as an event during the life of one individual, when these data are properly contextualized, it is possible to elucidate aspects of migratory processes from isotopically identified nonlocal individuals in archaeological contexts.

These theoretical and methodological advancements have contributed to better understandings of migration in Maya archaeology. As reviewed below, Maya migration has long been informed by archaeological and biodistance studies and despite the challenges associated with analyzing Maya skeletal collections, to date 50 published articles and chapters in edited volumes and 14 unpublished graduate theses and dissertations have successfully utilized isotope analysis to investigate human and animal movement to Maya sites. Initial isotopic studies not only established this technique in Maya archaeology, but also contributed to the debate regarding the influence of individuals from

the Central Mexican site of Teotihuacan in the Maya region (Buikstra et al. 2004; Price et al. 2010; White et al. 2000, 2001; Wright 2005a, 2005b, 2012; Wright and Bachand 2009; Wright et al. 2010). Subsequent studies have further developed these techniques, and interdisciplinary research that incorporates isotopic analyses has contributed to understandings of identity, social organization, and interaction within and beyond the Maya region in both prehispanic and Colonial periods (Freiwald et al. 2014; Cucina et al. 2015; Olsen et al. 2014; Ortega-Muñoz et al. 2019; Price et al. 2018a, 2018b; Sierra Sosa et al. 2014; Somerville et al. 2016 Suzuki et al. 2018; Tielser et al. 2010; Trask et al. 2012).

2.1 Migration in (Bio)archaeological Thought

Change in theoretical orientations have influenced archaeological conceptualizations of migration (Adams et al. 1978; Cabana 2011; Chapman and Hamerow 1997a; Chapman 1997; Clark 1994; Hakenbeck 2008; Kristiansen 1989; Peregrine et al. 2009; Sellet et al. 2006). Parallel developments in bioarchaeological methods and theory have been identified (e.g., Agarwal and Glencross 2011; Armelagos and van Gerven 2003; Ellison 2018; Hens and Godde 2008; Márquez-Grant et al. 2016; Walker 2008; Zuckerman and Armelagos 2011), but bioarchaeological conceptualization of past human movements have not been similarly evaluated (but see Meiggs and Freiwald 2014). The purpose of the following review is not to critique various models applied in archaeological understandings of migration, but rather to demonstrate how conceptualizations of past human movements reflect dominant theoretical perspectives and available methodology in both archaeology and bioarchaeology.

2.1.1 Conceptualizing Migration in Archaeology

Prehistoric archaeology developed in the nineteenth century as a rationalist study of cultural evolution based on Enlightenment ideals that equated technological progress identified in material culture to social and moral evolution. Cultural evolutionary archaeologists grouped past peoples based on their material culture, who were then ranked not just chronologically but also according to their perceived level of advancement with clear racial biases and motivations (Trigger 2006). Archaeological groups perceived as more advanced could independently develop, although Indigenous societies were viewed as static, and evidence of culture change in the archaeological record was thus attributed to prehistoric migrations (Trigger 2006:207).

In the late nineteenth century, culture-historical archaeology developed as a response to challenges to the benefits of technological progress and increasing nationalism and racism, and placed ethnicity as the driving factor that shaped human history (Trigger 2006:211). Culture-historians rejected evolutionism and proposed that because innovation was rare in the past, ideas spread from a single place of origin through culture contact and exchange (i.e., diffusion) or replacement (i.e., migration) (Trigger 2006:217-221). The opposition to evolutionism also fit well with concepts developed by cultural anthropologist Franz Boas, who emphasized cultural relativism and viewed the ethnographic culture as a basic unit of study (Stocking 1966). Ongoing archaeological research had also revealed temporal changes that could not be simply explained by the replacement of one group of people by another and archaeologists instead argued diffusion was the driving force behind culture change, as proposed by Boasian anthropologists (Trigger 2006:279). Other cultural-historical archaeologists such as Gustaf Kossinna and V. Gordon Child assumed that

material culture was produced by distinct ethnic groups (Trigger 2006:308). Kossinna (1911), however, rejected the role of diffusion in the spread of material culture in favour of migration, as he viewed inferior groups as being incapable of adopting cultural aspects from superior ethnic groups (Trigger 2006). Child (1925) accepted Kossinna's basic concept of culture but without the racist undertones and proposed that both migration and diffusion caused material culture change that could be identified archaeologically.

However, migration was not systematically assessed as it was in related disciplines (e.g., Ravenstein 1885, 1889) nor was it defined. Instead it was uncritically invoked as an atheoretical explanation for the sudden appearance of "foreign" styles of artifacts, architecture, site distributions, funerary patterns, and linguistic traits (Adams et al. 1978). While individuals buried with "foreign" funerary objects were identified as migrants, the primary methods involved comparing available data sets of material culture and human remains, which permitted the identification of migration at the population level. In this context, migration was conceptualized as an event involving the rapid, long-range, unidirectional, and permanent relocation of a substantial number of people into a new area at the expense of local populations (Adams et al. 1978:486; Chapman and Hamerow 1997b; Childe 1950; Clark 1994:306, 309-310; Rouse 1986). Although other researchers argued that the same data could be explained by either *in situ* cultural evolution or the diffusion of cultural elements from one group to another without the movement of people, diffusionism via migration remained the primary explanatory principle for archaeological material culture change well into the twentieth century (Chapman 1997:12; Trigger 2006:217).

By the mid-twentieth century, various scholars demonstrated the inadequacies inherent in the culture history approach, and processualism emerged as the dominant

paradigm in North American anthropologically oriented archaeology. Processual archaeology, which developed from the cultural evolutionary approach, stressed the importance of the scientific method and hypothetico-deductive models. Adherents of this theoretical paradigm perceived diffusion and migration as inadequate explanations for culture change because people could adopt material culture independent of migration. Processualists critiqued cultural history approaches for perceiving cultures as bounded, homogenous, and normative (Chapman and Hamerow 1997a:4), and so adopted alternative explanatory strategies based on *in situ* cultural development (e.g., Binford 1968; Renfrew 1973). This followed critiques from archaeologists such as Clark (1966:189), who argued that migration should be demonstrated archaeologically and not simply assumed. As a result, North American processualist archaeologists largely avoided migration as conceptualized in the culture historic framework altogether (Adams et al. 1978). This was not, however, the case for all researchers, particularly in continental Europe and Eurasia, where archaeology is viewed as a historical discipline and migration continued to be an important research topic (Härke 1998; Frachetti 2011; see also Burmeister 2000:539; Chapman 1997:12-13). Researchers working under the processualist paradigm avoided migration in part because they lacked methods to identify it, but also because they rejected the cultural historic approach and instead adopted evolutionary paradigms (Burmeister 2016:43).

Processual archaeologists did, however, accept *mobility* as a defining characteristic of hunter-gather groups. Although often conflated with migration, mobility refers more broadly to the ability of a person or people to move (Close 2000:49-50; Inomata 2004:179). In archaeological contexts, mobility traditionally refers to non-sedentary hunter-gatherer

groups who frequently move their settlements/camps (Kelly 1992; Kent 1992; Sellet et al. 2006), rather than the permanent relocation of individuals within sedentary societies. One way in which processual mobility studies differentiated themselves from culture historic conceptualizations of migration was to develop typologies and specific definitions for differing types of mobility (Binford 1980).

During the 1980s, archaeologists began to criticize processualist approaches for attempting to generalize human experiences and instead focused on the influence of social phenomena and individual experiences in the past (see Cowgill 1993; Hodder 1985; Patterson 1990). Rather than adopting a single overarching paradigm, postprocessual approaches rejected universal laws and general processes and turned to the historically contingent character of past phenomena and social aspects of identity (e.g., gender, age, status, ethnicity etc.) in conceptualizations of past cultural phenomena (Trigger 2006:445-478), including human movement (Chapman and Hamerow 1997a:4). Such frameworks allowed postprocessual researchers to avoid the ethnocentric perspectives that dominated previous archaeological interpretations (Cobb 2005; Stein 2002). The postprocessual paradigm also encouraged reflexivity, and it is now recognized that the life experiences of researchers influence their interpretations of human behaviour in the past, including migration (Burmeister 2016; Champion 1990:215; Härke 1998; Kristiansen 1989, 2004). While postprocessualism is certainly not embraced by every archaeologist, this paradigm shift prompted researchers to revisit the potential of studying human movement in archaeological interpretations of the past (Anthony 1990, 1992; Champion 1990; Kristiansen 1989; Osborne 1991; Otte and Keeley 1990).

Resistance to the reintegration of migration in archaeology was fueled by academic emphasis on economics as a driving force of modern migration at that time, as well as the assumption that generalized models of migration based on modern, globally connected populations were inappropriate for interpretations of population movement among preindustrial societies (Chapman and Dolukhanov 1992; Clark 1994; Clark and Lindly 1991; Rouse 1986:161-163). Others, however, have convincingly argued that although the scale and scope of migration has changed, there are sufficient similarities in past and present population movements to allow their patterns and dynamics to be compared (Anthony 1990, 1992; Baker and Tsuda 2015b:4; Burmeister 2000; Cabana and Clark 2011a:4; Cameron 1995; Campbell and Crawford 2012:2; Chapman 1997; Duff 1998:32; Manning 2006:48; O'Rourke 2012; Sanjek 2003; Tsuda 2011). It is now understood that perspectives of migration from other fields not only contribute to archaeological understandings of this process, but that archaeological studies also offer an important framework for contextualizing modern migration (Baker and Tsuda 2015b; Cabana and Clark 2011a:4; Campbell and Crawford 2012; Cresswell 2010; Sanjek 2003).

Proponents of the study of migration in archaeology argue that traditional archaeological definitions ignore the processes of migration that have long been observed in related disciplines (e.g., Brettell and Hollifield 2000a; Ravenstein 1885; 1889) and have encouraged the incorporation of theoretical concepts and models from studies of modern migrations (Anthony 1990, 1992; Burmeister 2000; Kristiansen 1989). Such research recognizes migration as a complex process, with a multitude of societal, cultural, political, economic, and biological aspects, that was primarily undertaken by small groups of people or individuals (Anthony 1990; Burmeister 2000; Smith 2014; Tsuda 2011:321). Negative

(push) conditions in the home region and positive (pull) conditions in the destination, combined with acceptable transportation costs and information about the destination known from previous migrants through established communication channels lead to migration (summarized in Anthony 1990:899). Long-term or permanent migration patterns can include stepwise migration, chain migration, return migration, and channelized migration, all of which are interrelated, and short term or temporary migration may include internal migration (e.g., tourism, pilgrimage), as well as seasonal migrations between two regions (transhumance, pastoralism, etc.).

Ass seen in Figure 2.1, variation in migration in different contexts is caused by numerous factors, including permanency (temporary or permanent), directionality (unidirectional or multidirectional), temporality (one generation or multigenerational), spatial extent (long or short distance; within or among regions), and the mode of the movement itself. Other factors relate to reasons people moved, ranging from how (voluntary/forced), and why (warfare, climate change), to characteristics of migrants themselves, including their ages, genders, or social situations, (Cabana and Clark 2011a; Champion 1990; Kardulias and Hall 2007; Kristiansen 1989; Sjögren et al. 2016:3). Many include ecological and economic factors, as well as the independent ones, such as time, physical constraints of the human body, load carrying, topography, and access to resources during travel. Sociocultural factors such as symbolic navigation are also important, as are terrestrial navigation, geographical knowledge, and the relationships among individuals and communities (Cameron 2013; Murrieta-Flores 2009), although not all may be identifiable archaeologically.

Nuanced frameworks are also being incorporated into multidisciplinary research,

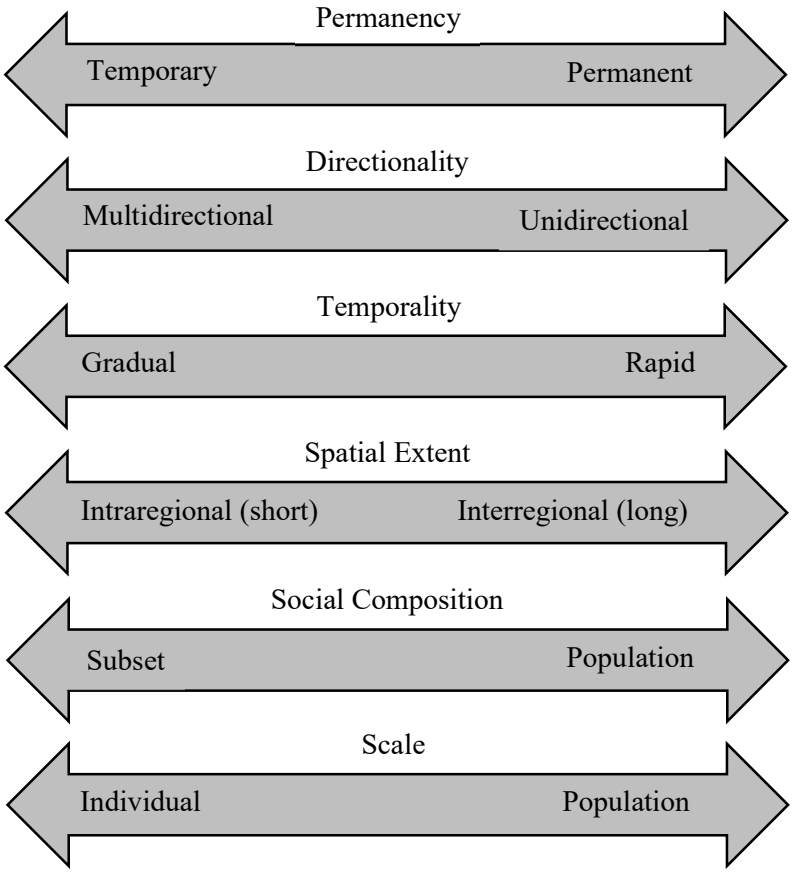

Figure 2.1: Spectrum of aspects that comprise the process of migration.

such as the concept of diaspora, wherein diasporic communities initially disperse from a host society, but maintain continuous social or spiritual links with their homelands for generations (Baltus and Baires 2020; Eckardt and Müldner 2016; Emerson et al. 2020). Finally, researchers are exploring other forms of movement that existed in past societies, such as captive taking, fission and fusion, and random demographic processes (Cameron 2013). Overall, now that the structures of specific prehistoric population movements are beginning to be understood, other aspects of migration, such as identity and the impact of migrants on cultural dynamics and change in both the sending and receiving regions can be explored (Batiuk 2013; van Gijseghem 2013).

2.1.2 Conceptualizing Migration in Bioarchaeology

Bioarchaeology is an interdisciplinary subfield of biological (physical) anthropology[3] that studies human remains from archaeological contexts to reconstruct past behaviour (Larsen 2014), including migration. Biological anthropology began in the nineteenth century, and much like early archaeological studies, the first biological anthropological studies focused on description and the development of racial classifications for living and skeletal humans (Marks 1995). The few skeletal studies conducted at that time consisted of measuring the skull using craniometric or anthropometric techniques that related brain size to hierarchies of racial types (e.g., Morton 1839) with little interest in evolution or scientific hypothesis testing (Little and Sussman 2010:14). Racial categories were based on physically visible traits as well as non-biological, socially constructed racial attitudes (Hagen 1996:569) and racial prejudice was heavily influenced by political and cultural factors that contributed to both social and scientific perspectives at that time (Brace 2010:25; Ortner 2010:103). Some, however, attempted to differentiate physical anthropology from racism (e.g., Boas 1934; Hooton 1936; Montagu 1942).

These early osteological studies were central to the use of migration as an explanation for culture change because if "the spatial (and temporal) distribution of cranial types could be assumed to result from the movement of culturally and biologically distinct

[3] The identifiers "physical" and "biological" are often used interchangeably when referring to the diverse subfield of anthropology that applies archaeological theory to address the biological basis of human behaviour, diversity, and evolution (Turner 2005). However, the former term is reminiscent of the prejudice beliefs that emphasis physical traits of human beings that motivated the origins of this subdiscipline (see the text). Therefore, biological anthropology is used here, as it is not only more inclusive and applicable to diverse areas of research, but it also demonstrates "the [sub]discipline's emphasis on the population and its biocultural aspect in addition to the evolutionary history of the entire species as the object of study, rather than on physical types of humans" (DiGangi and Moore 2013:7; see also Martin et al. 2013:31).

peoples, both biological and culture history could be reconstructed from similarities and differences in cranial morphology" (Adams et al. 1978:513). Although researchers such as Boas (1912) quickly realized that the shape of the cranial vault is influenced by both genetic and environmental factors, such uncritical and racist craniometric studies persisted into the mid-twentieth century (see Adams et al. 1978: 514-522; Walker 2008:8-9). Biological anthropologists have since acknowledged and critiqued the racism and cultural biases that characterized these early biological anthropological studies (Armelagos and Goodman 1998; Armelagos and van Gerven 2003; Blakey 1998). Although skeletal measurements continue to form the basis of quantitative research, such studies are informed by anthropological and biological theory and employ a biocultural model that uses metric measures to address the influences of environment and culture on skeletal growth and development (Martin et al. 2013:28-31).

The "New Physical Anthropology" advocating theory-driven research and hypothesis testing subsequently emerged (Washburn 1951) but did not take hold until the 1960s (see Zuckerman and Armelagos 2011). The term bioarchaeology, or the interdisciplinary study of human remains from archaeological sites, was also first coined during this time (Buikstra 1977). This period represents the first wave of theoretical engagement in bioarchaeology (Agarwal and Glencross 2011:1-2) and parallels the interest of processual archaeologists in universal models and *in situ* cultural development (e.g., Lasker 1970). As with processual archaeology, the ecological approach in anthropology greatly contributed to bioarchaeological concepts in the latter half of the twentieth century (Zuckerman and Armelagos 2011:18).

Interest in understanding population demographics from archaeological skeletal remains (e.g., Haviland 1967) continued to use morphological similarity in cranial types but substituted "gene flow" for migration and began to use increasingly complex statistical analyses (Adams et al. 1978:516). However, influenced by processualism, these studies focused on the analysis of *in situ* biological evolution (Adams et al. 1978:517) and considered populations as stationary (i.e., closed to both inbound and outbound migration), which ignored the impact of human movement on demographic reconstructions (Wood et al. 1992).

Following the development of postprocessual archaeological discourse, the second wave of bioarchaeological theoretical engagement largely involved critical assessment of assumptions and methodology (Agarwal and Glencross 2011:2). For example, researchers began to question whether archaeological skeletal assemblages accurately represent the populations from which they derive (Bocquet-Appel and Masset 1982; Jackes 2011; Wood et al. 1992). Novel scientific techniques, including isotopic analysis of human migration, were also critiqued for being primarily descriptive rather than theorizing explanations for the processes observed (Armelagos and Van Gerven 2003; Hens and Godde 2008), as were individual-based mortuary studies (Gillespie 2001).

This was followed by the third and most recent wave of theoretical engagement in bioarchaeology, which seeks to contextualize skeletal studies, including those that utilize novel techniques, through the integration of biological, behavioral, ecological, and social research (Agarwal and Glencross 2011:3; Zuckerman and Armelagos 2011:19). As in archaeology, bioarchaeologists are also beginning to explore the broader sociocultural impacts of migration, including how local and nonlocal individuals negotiated identity

(e.g., Knudson 2011; Knudson and Stojanowski 2008, 2009; Zakrzewski 2011). Archaeological isotope studies are also beginning to engage with theorizations of migration in the past, as recently evidenced by Eckardt and Müldner (2016), who contextualized isotopic data using epigraphic and material culture to interpret migration in Roman Britain within the framework of diaspora. Both the second and third wave of bioarchaeological theoretical engagement reflect the development of postprocessualism in archaeology that challenged the infallibility of scientific methods and replaced universal models with more context-driven research focused on the social aspects of identity of people, including those of migrants, in the past.

2.2 Methodological Implications for Conceptualizations of Migration in Bioarchaeology

Methodological approaches to migration in archaeology should be founded on theoretical understandings of migration as a process (Anthony 1990, 1992), as developments in method and theory are interconnected (Burmeister 2000:540; Adams et al. 1978:523). Indeed, methodology based on solid theoretical foundations has led to nuanced understandings of past human movements (e.g., Burmeister 2000; Close 2000), just as the expansion of data sets and advancement of methodological approaches for identifying this phenomenon in the archaeological record have refined theoretical understandings of what constituted migration in the past and its interpretation in specific contexts (Hakenbeck 2008; Scharlotta et al. 2018).

Archaeological conceptualizations of migration are also linked to the scale of analysis, which is largely dictated by available data sets and methods. Foreign grave goods included in funerary contexts have been used to identify individuals as potential migrants

(Burmeister 2016; Kristiansen et al. 2017:336), although it is possible for people to adopt material culture independently of migration (Hodder 1982; Price et al. 2010; White et al. 2001; Wright 2005b). Other methods for identifying migration in archaeological contexts based on the material record preclude the identification of individual movement, as only long-term population movements over large distances that create significant change in material culture, settlement patterns, language, or genetics are visible (Adams et al. 1978:488-489; Anthony 1990:901-902; Beekman 2019; Beekman and Christensen 2003:154-155; Bolnick 2011; Burmeister 2000:547; Cameron 1995; Clark 2001; Huntley et al. 2016; Tsuda 2011; Tsuda et al. 2015:19). Essentially, it is "the social practices created or disturbed by a migration rather than migration itself that are visible in the archaeological record" (Beekman and Christensen 2011:147). Archaeologists have therefore struggled with developing a means of unequivocally identifying the varying types and scales of human movement from the archaeological record, although a variety of techniques have been explored (e.g., Abell 2014; Burmeister 2000; Close 2000; Crawford 1997; Emerson and Hargrave 2000; Hamerow 1997; Inomata 2004; Otte and Keeley 1990; Peregrine et al. 2009; Zakrzewski 2011). Consequently, archaeologists have adopted macrolevel techniques to analyze the aggregate culmination of individual movements that occurred over long periods of time (Burmeister 2000:547; Clark and Lindly 1991:582; Leppard 2014:486-487).

Fortunately, theoretical paradigm shifts in archaeology have been accompanied by methodological advancements (Kristiansen 2014, 2017; but see Armelagos and Van Gerven 2003:60). In archaeological studies of human movement, the reconceptualization of what constitutes migration in past cultures have been subsequently validated by

osteological (biodistance), biogeochemical (isotopic), and genetic studies in bioarchaeology (Frachetti 2011; Meiggs and Freiwald 2014; see also Section 2.3.1).

2.2.1 Biodistance Analyses of Migration

Biological distance, or biodistance, refers to the comparison of phenotypic traits (morphological and metric skeletal and dental characteristics) among skeletal populations to identify their genetic relatedness. This in turn can speak to population history and structure within and among archaeological culture areas, as shared ancestry and gene flow cause different skeletal populations to be morphometrically similar (Hefner et al. 2016).

While physical anthropology was primarily focused on using metric and nonmetric aspects of the cranium and dentition to arrange human groups into typologies throughout the 1930s and 1940s (Hefner et al. 2016), this changed with the introduction of the New Physical Anthropology by Washburn (1951). The emphasized hypothesis testing, biochemical mechanisms in human evolution, and other processual perspectives of human evolution led biological anthropologists to apply increasingly complex statistical analyses to biological data derived from archaeological skeletal remains at the population level to address biocultural aspects of past societies (e.g., Buikstra 1977). Advances since the 1970s have now grounded metric and nonmetric analyses of cranial and dental remains from archaeological skeletal assemblages in anthropological and biological theory and when coupled with robust statistical techniques, these methods provide insights into the complex relationships between and within human populations (Hefner et al. 2016). Advances in biodistance studies have also been accompanied by developments in the analysis of modern and ancient DNA that have revived genetic-based understandings of inter- and intra-

population relationships (e.g., Bolnick 2011; Fix 2011; Hervella et al. 2015; Renfrew 2000). Both types of genetic techniques interpret biological affinity as the result of gene flow, which is equated with the migration of people, whereas genetic drift causes isolated populations to be genetically dissimilar (Raghavan 2018).

Biodistance and genetic studies are also typically conducted at the level of the population, which allows migration to be studied within and between regions. However, such an approach risks presenting "past peoples as homogenous and indistinguishable" (Geller 2012:257). With increasing interest in individual identities and "peopling the past" (Buikstra 2006:xix), bioarchaeologists have also pursued various means of conducting research at the level of the individual (e.g., Stodder and Palkovich 2012). Isotopic analyses specifically address microscalar migration in the past by directly identifying nonlocal *individuals* in a skeletal collection. As such, "[s]table isotope analysis provides a 'bottom-up' evidence-driven approach to mobility, and it thus has the potential to bridge [t]he gap between large-scale patterns of mobility and the small-scale effects of mobility on individuals and their burial contexts" (Hakenbeck 2008:19; see also Burmeister 2016:44; Laffoon 2013:426; van Dommelen 2014:479).

2.2.1 Identifying Nonlocal Individuals using Isotopic Analyses

Strontium ($^{87}Sr/^{86}Sr$) and stable oxygen ($\delta^{18}O$) isotopes are most commonly analyzed in studies of past migrations, and their application in archaeology has been extensively reviewed and critiqued elsewhere (Bentley 2006; Lightfoot and O'Connell 2016; Makarewicz and Sealy 2015; Montgomery 2010; Pederzani and Britton 2019; Scherer et al. 2015; Schwarz et al. 2010). Stable sulfur isotope ($\delta^{34}S$) analysis has also been

established as a means of investigating archaeological migration (Nehlich 2015) but has only recently been applied in Maya archaeology (Awe et al. 2017; Green 2016; Rand and Grimes 2017; Rand et al. 2020a, 2020b, 2021a, 2021b).

The utilization of isotopic analyses for identifying nonlocal individuals is dependent upon the spatial heterogeneity of the isotopic values from subsistence resources among different regions. The isotopic compositions of bones and teeth are derived from an individual's diet and drinking water, which in turn reflect those of the local environment (Bentley 2006; Longinelli 1984; Nehlich 2015). Based on the assumption that people obtained the majority of their food and water near where they lived, nonlocal individuals are identified as those whose bone and/or tooth enamel isotope values differ from those expected in the local environment. In the Maya region, there is sufficient variation in biologically available (bioavailable) $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values among different regions to identify nonlocal individuals, and local isotopic baselines that characterize regional variation have been developed for much of this area (Hodell et al. 2004; Freiwald 2011a; Lachniet and Patterson 2009; Miller Wolf and Freiwald 2018; Price et al. 2007, 2008, 2010, 2015; Thornton 2011; Trask et al. 2012). Preliminary evidence indicates that lead isotopes (Sharpe et al. 2016) and $\delta^{34}S$ values (Green 2016; Rand and Grimes 2017) may also provide insights into human migration in the Maya region. In some cases, stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope analyses, which are most commonly used to examine diet, may also help identify nonlocal individuals as those with atypical diets (Gerry and Krueger 1997; Hedman et al. 2002; but see Schwarcz et al. 2010:340), particularly when combined with other isotopic data (Freiwald 2011a; Price et al. 2014; Suzuki et al. 2020; Wright et al. 2010; Wrobel et al. 2017).

There are several methods for establishing whether individuals migrated to the sites where they were buried using the isotopic values of their tissues (see Appendix A for a detailed discussion). For example, a difference in the isotope values of bones and teeth from the same individual that form at different stages of life indicate whether he or she migrated from isotopically distinct regions in the intervening period between tissue formation (Agarwal 2016; Buikstra et al. 2004; Hrnčíř and Laffoon 2019; Montgomery 2010; Montgomery et al. 2000; Schroeder et al. 2009; Schweissing and Grupe 2003; White et al. 2000). Individuals with isotopic values that fall beyond the range of local baseline values developed from archaeological and modern flora, fauna, water, and geological samples (Grimstead et al. 2017; Hodell et al. 2004; Lachniet and Patterson 2009; Makarewicz and Sealy 2015; Price et al. 2002; Sillen et al. 1998) as well as published values (Lightfoot and O'Connell 2016; Price et al. 2007, 2008, 2010) are also interpreted as having moved to their place of burial. When baseline and comparative human isotopic data from other sites are unavailable, nonlocal individuals may also be identified as those whose isotopic values are statistical outliers from the human data set of interest (Burton and Hahn 2016:119; Freiwald 2011a; Laffoon and Hoogland 2012; Lightfoot and O'Connell 2016; Montgomery et al. 2007; Knudson 2011; Wright 2005a; Chapters 4 and 5).

The postmortem alteration of the chemical composition of bone, or diagenesis, is another concern in isotopic studies of human movement, as interpretations are dependent on the preservation of biogenic (i.e., those formed during life) isotope values. While criteria have been established for evaluating whether the $\delta^{34}S$ values of the organic portion of bone (i.e., collagen) have been diagenetically altered (Nehlich and Richards 2009), it is more difficult to evaluate the preservation of the mineral component of bone (i.e., bioapatite).

Because bone is less mineralized and therefore more susceptible to diagenetic alteration than is enamel, many researchers prefer to sample tooth enamel for strontium and stable oxygen isotope analysis (Budd et al. 2000; Hoppe et al. 2003; see Appendix A).

Another concern is the principle of equifinality, whereby multiple regions share similar isotopic signatures, precluding the identification of the exact place from which a nonlocal individual originated (Laffoon 2013:420). However, establishing finer-grained isotopic baselines and analyzing multiple isotopes from the same individual have contributed to narrowing down potential places of origin (Freiwald 2011a; Laffoon 2013:420), and the nearest isotopic region with values comparable to those of a nonlocal individual is typically parsimoniously proposed as the likely place of origin. Furthermore, because isotopic analyses may only detect the movement of individuals from isotopically distinct geographical areas, this technique will underestimate the number of nonlocal individuals who migrated from isotopically similar regions (Eckardt and Müldner 2016:209; Freiwald 2011a:303).

Despite these limitations, when interpreted in conjunction with other lines of evidence, isotopic analyses of multiple individuals can provide information about the permanency, directionality, temporality, spatial extent, social composition, and scale of migration into a community. While it is not possible to detect the intent of an individual to permanently relocate, the analysis of multiple isotopes of the tissues from the same individual that form at different ages (e.g., tooth enamel and bone) and the analysis of multiple samples from the same tooth that form at different times (i.e., intra-tooth analysis) can also provide insights into the length of time an individual resided in an area, whether he or she moved from isotopically distinct regions multiple times during his or her life, and

potential areas from which he or she may have originated. However, isotopic analysis cannot evidence short term mobility, such as seasonal rounds, pilgrimages, or trips (e.g., Sellet et al. 2006), because these would be masked by environment isotopic values derived from more permanent places of residence.

In terms of temporality, isotopic analyses detect relocations during the lifetime of one individual. However, when combined with chronological evidence from ceramic sequences and radiometric dating the analysis of multiple individuals from different time periods can provide insights into the frequency of migration over time, which in turn can speak to the temporality of the migration process in specific contexts (e.g., Suzuki et al. 2020). Similarly, although the spatial extent of migration is difficult to assess because places of origin are difficult to determine, the development of isotopic baselines throughout a region combined with the analysis of multiple individuals can provide insights into the regions from which nonlocal individuals originated and whether nonlocal individuals arrived from multiple different areas (Freiwald 2011a; Freiwald et al. 2014; Miller Wolf and Freiwald 2018; Price et al. 2014; Somerville et al. 2016). Finally, the analysis of multiple individuals of varying ages, sexes, and statuses allows for the social profile of nonlocal individuals to be investigated, as well as the scale of migration based on the percentage of individuals who are identified as nonlocal (Freiwald 2011a, 2011b; Miller 2015; Ortega-Muñoz et al. 2019; Price et al. 2018a; Suzuki et al. 2018).

Overall, isotopic analyses of human remains are invaluable tools in archaeological reconstructions of human migration. This is because isotopic analyses allow migration to be directly identified from the physical remains of an individual, while avoiding “the associative inferences between material culture, language, and people that are necessary to

migration arguments in archaeology and linguistic anthropology" (Knudson 2011:232). Thus, isotope analysis can provide proof of archaeological migration unobtainable using other techniques. Although isotopic values cannot themselves identify the factors, processes, and consequences of migration on isotopically nonlocal individuals, their place(s) of origin, or the receiving community, insights into these aspects can be elucidated through contextualizing isotope results using multiple lines of evidence. Thus, by necessity, isotopic studies of human remains are embedded within broader (bio)archaeological analyses of human migration and are inherently interdisciplinary.

2.3 Defining Migration in (Bio)archaeological Isotope Studies

Despite theoretical and methodological advances, the uncritical utilization of terms such as migration and mobility without proper definition in archaeological discourse has caused difficulties in the study of past human movements (Cabana and Clark 2011a; Champion 1990:214; Clark 1994:309; Clark and Lindly 1991; Close 2000:49-50). Although operational definitions of migration and other types of human movement are necessary before these concepts can be identified and interpreted archaeologically, clear definitions have not been forthcoming. For example, although it was often cited as an explanation for culture change, culture historians never explicitly defined migration. Much later, migration was clearly defined in an archaeological sense as "the simultaneous and permanent movement of substantial numbers of people … which might be expected to leave measurable traces in the cultural, the linguistic, and the skeletal record of peoples or areas" (Adams et al. 1978:486). Thus, human migration was viewed as only archaeologically

visible at the population level (Burmeister 2000:547; Clark and Lindly 1991:582; Leppard 2014:486-487).

Alternative terms have also been proposed in the literature, most of which address the spatial and temporal scale, intent, permanency, and social impact of population level migration. For example, *population movement* was originally defined as the long-distance movement of a large wave of people into a new area at the expense of local inhabitants (Rouse 1986:176) but is now used in place of migration because it is considered neutral and encompasses the diversity inherent in various types of human movements (Kristiansen 1989:219). Other terms instead imply the result of migration, such as *colonization*, wherein people establish themselves (permanently or semi-permanently) in a new area (see Giovas and Fitzpatrick 2014:570; Rockman 2003) and *invasionism*, which "envisions hostile migrations, either temporary or permanent, the effect of which is primarily negative: sudden culture loss and/or the abandonment of sites" (Adams et al. 1978:488).

Borrowing from related disciplines, typologies of various forms of human movement (Aimers 2015; Wells and Stock 2012:36-39) and the people who moved (e.g., Tsuda et al. 2015:21) have also been developed. While such typologies are useful heuristic devices for directing research in living populations (Brettell 2000:102), the incomplete nature of the archaeological material record precludes the classification of ancient migration into discrete categories (Nelson and Schachner 2002). Furthermore, the creation of these typologies and the definitions associated with the terms included therein hazard the incorporation of theoretical conclusions into definitions and the projection of modern biases onto archaeological societies (Kardulias and Hall 2007:5).

Mobility has thus been proposed as a more neutral term for discussing past human movements (Hakenbeck 2008:19; Leary 2014). In archaeology, the term mobility has conventionally referred to non-sedentary hunter-gatherer groups who frequently moved their settlements/camps (e.g., Kelly 1992; Sellet et al. 2006). Although studies of sedentary archaeological cultures have instead focused on permanent relocations from a homeland to a distant location (see chapters in Baker and Tsuda 2015a; Cabana and Clark 2011b; Crawford and Campbell 2012), mobility is fundamentally defined as a physical movement from one place to another that involves the embodied practice of movement within specific contexts (Beaudry and Parno 2013; see also Creswell 2010:19). In Mesoamerica, for example, mobility within a local area was likely high among lower status Aztec people (Smith 2014), and Maya of lower status had the ability to "vote with their feet" in times of political or environmental stress (Inomata 2004; Webb 1973:401). Thus, "[n]o society is sedentary … people just move in different ways" (Kelly 1992:60; see also Sheller and Urry 2006). While mobility is a helpful framework for discussing the movement of people (and things) in past societies without invoking a specific type (i.e., immigration, emigration, transhumance, pilgrimage, trade, diaspora, exogamy, etc.) and is a popular alternative to migration commonly used in isotope studies of archaeological cultures (e.g., Rand et al. 2020a; Scharlotta et al. 2018; see also Chapter 5), it is unspecific and cannot speak to the migration process in a sociocultural sense.

With the nuanced understanding of migration as a complicated sociocultural process of varying scales and temporal and spatial extents, others have argued for a redefinition of migration itself in archaeology (Cabana and Clark 2011a; Hofman et al. 2014:595; Tsuda et al. 2015). For example, Tsuda and colleagues define migration as "the

movement of people across significant *socio-cultural, political, or environmental boundaries* that involves uprooting and *long-term relocation*" (2015:19, original emphasis). While it is important to differentiate migration from temporary movements (i.e., visits, pilgrimage, seasonal rounds), such a definition continues to emphasize the "large-scale, long-distance, and long-term nature" of migrations and excludes "internal, localized movements within a cultural/political/environmental boundary" (Tsuda et al. 2015:19). To avoid assumptions about the causes or consequences of migration and to acknowledge their multiscalar nature, Cabana and Clark have proposed a minimum definition of migration as "a *one-way residential relocation to a different "environment" by at least one individual*" (2011a:5, original emphasis), that is intended to be expanded upon within individual research contexts. Although these minimal definitions continue to focus on the aspect of permanency in relation to migration with terms such as "long-term relocation" and "one-way", they still offer the most grounded yet flexible means of conceptualizing the dynamic process of past human migrations.

Isotopic studies of archaeological migration have been similarly plagued with a lack of definition, uncritical appropriation of migration and related terminology, and the conflation of terms (Scharlotta et al. 2018:867). For example, isotopic analyses are sometimes referred to as *proveniencing* studies (e.g., Suzuki et al. 2020), although this term is inappropriate given that an individual's provenience (place of origin) cannot be determined isotopically due to equifinality. Similarly, the term *residential mobility* refers to movement within urban areas in modern migration scholarship (Quigley and Weinberg 1977; Zimmer 1973) and was originally adopted to define the movement of a group of hunter-gatherers from one camp to another in archaeological discourse (Binford 1980).

Despite the differing meanings of residential mobility, this term is frequently used to refer generally to isotopically identified human movement in isotopic studies (e.g., Knudson and Price 2006; Laffoon 2013; Price et al. 1994; Somerville et al. 2016). Some bioarchaeologists have therefore suggested the use of the term *relocation* in place of residential mobility to refer to the isotopically identified movement of an individual over any distance (after Knudson 2011:231).

Although the reconceptualization of migration in archaeology has been driven by both theoretical and methodological advances, *migration* is rarely defined in archaeological isotope studies (but see Freiwald 2011a:16; 2020:204, 2021). The minimal definition of migration proposed by Cabana and Clark (2011a:5) is appealing in isotopic studies at the individual level because it acknowledges the multiscalar nature of past migrations while providing a framework in which to conceptualize migration rather than mobility in general. The characterization of migration as the relocation across a boundary[4] (e.g., Anthony 1990:902; Cabana and Clark 2011a:6; Tsuda et al. 2015:19) is also relevant, as isotopic analyses detect individuals who have moved from isotopically distinct regions. Thus, an *isotopically detectable migration* is minimally defined here as *the relocation of a sampled individual to an isotopically distinct environment at least once during his or her life* (*c.f.* Freiwald 2011a:16; Somerville et al. 2016:157). In this sense, migration is identified as an event within one person's life rather than a process, but when properly contextualized as discussed above, it is possible to elucidate aspects of migratory processes from isotopically

[4] Note that boundaries are defined as separating "different environmental, cultural, linguistic, economic, or political areas or zones and generally permit more flexible movement across them", whereas a border is "a type of boundary that delineates political territories, such as those found between nation-states, polities and empires" (Tsuda et al. 2015:20).

identified nonlocal individuals. As such, this is a minimum definition that should be expanded in specific archaeological contexts using archaeological, epigraphic, ethnohistoric, genetic, linguistic, osteological, and other data (*c.f.* Cabana and Clark 2011a).

It is also necessary to define the terminology used to describe the people who moved in the past. For example, modern *migrants* are individuals who have crossed an international political border (Brettell and Hollifield 2000b:20), although in archaeology migrant may refer to any person who has moved, regardless of the distance or boundaries involved. Other terms, such as *foreigner*, *alien*, *settler*, *colonist*, and *sojourner*, are less common in the archaeological isotope literature but imply aspects of the person moving that can mean different things to different researchers. Methodological limitations should also be considered in such definitions. Isotopic techniques, for example, identify individuals with statistically distinct values as having moved *to* an isotopically distinct area, and so only immigrants are isotopically visible in archaeological studies. Thus, in this study the term *nonlocal* refers to individuals whose isotopic values are statistical outliers from the sample population, whereas *local* individuals are those who fall within the statistically determined local range (Freiwald 2021).

However, just as people with nonlocal isotopic signatures may not have been understood as outsiders, an isotopically "local" individual may not have been considered a local member of the community because vast areas can exhibit similar isotopic values (i.e., equifinality; see Section 2.3.1). Isotopic boundaries among regions are also better understood as gradients or mosaics and may not correspond to the often archaeologically elusive perception of boundaries held by people in the past (Cabana and Clark 2011a:9).

Therefore, the terms nonlocal and local refer only to isotope values in this study, which may or may not reflect how individuals viewed themselves or were recognized by the receiving community (Knudson 2011:232). Fortunately, interdisciplinary research has begun to examine the identity of both isotopically identified nonlocal individuals and receiving communities in archaeological contexts (Freiwald et al. 2014; Cucina et al. 2015; Olsen et al. 2014; Ortega-Muñoz et al. 2019; Price et al. 2014, 2018a, 2018b; Sierra Sosa et al. 2014; Suzuki et al. 2018; Trask et al. 2012; Zakrzewski 2011).

2.4 Prehispanic and Colonial Period Migration in the Maya Region

Migration, as traditionally defined in archaeology, has been a common explanation of culture change in the Maya region, with many of the early studies suggesting the Maya themselves did not move but instead were invaded by more militaristic populations from Central Mexico. However, as elsewhere, the conceptualization of migration in Maya archaeology has changed over time. Developments in biological anthropological methods and theoretical understandings of migration have contributed to the increasing number of studies that have successfully applied isotopic analyses to address questions related to migration in Maya archaeology.

2.4.1 Initial Interpretations of Migration in the Maya Region

During the early and mid-twentieth century, migration, specifically invasion, was frequently cited as an explanation for culture change at the end of the Classic and Postclassic periods. For example, it was proposed that individuals from Central Mexico (e.g., the Toltecs) or "Mexicanized" Maya from the Gulf Coast of Veracruz, Mexico (e.g., the Putun or Itza) invaded Chichen Itza in the Northern Lowlands and sites such as Seibal

in the southwestern Peten region of present-day Guatemala (Morley 1946; Roys 1966; Sabloff and Willey 1967; Thompson 1966). These arguments were, however, based on (1) Indigenous and Spanish historical sources written centuries after the events in question (Cobos 2015:51); (2) biased conceptualizations that Classic Maya society comprised a peaceful priesthood that was susceptible to domination by militaristic groups from Central Mexico (Jones 1997); and (3) the presence of "foreign" material culture such as fine paste ceramics and artistic styles (Sabloff and Willey 1967). Although researchers such as Andrews (1960) provided evidence against these sensationalized invasion hypotheses over sixty years ago, it is only within the last few decades that they are beginning to be discredited in the archaeological literature with subsequent analyses of multiple lines of evidence. For example, interpretations of hieroglyphics at Seibal now indicate the site was instead revitalized by Wat'ul Chatel, a Terminal Classic representative of Ucanal, another Maya site to the east (Tourtellot and González 2004) and the large-scale trade of fine wares manufactured in the Gulf Coast region throughout the Maya region was more complex than previously thought (Jiménez Alvarez 2015).

With the reconceptualization of migration that accompanied the rise of postprocessualism in archaeology, the deciphering of Mayan texts that record the movement of Maya elite, and the development of novel techniques for identifying nonlocal individuals, understandings of the movement of people and cultural interaction within and beyond the Maya region have changed drastically. This is particularly well demonstrated in isotopic contributions to understandings of the relationship between the Maya and individuals from Teotihuacan in Central Mexico. While nuanced studies of human movement among the Maya continues to be investigated using archaeological data (Aimers

2015; Arnauld et al. 2017; Rice 2015; Scherer et al. 2018), bioarchaeological approaches including biodistance studies and isotopic techniques have been very useful in re-evaluating and further contributing to archaeological perspectives on prehispanic and Colonial period Maya migration.

2.4.2 Bioarchaeological Evidence for Maya Migration

Initial biological studies of Maya skeletal assemblages were focused on description and development of typologies (e.g., Hooton 1940). Following predominant theoretical trends posited by the New Archaeology and New Physical Anthropology, biological anthropology assessments of Maya skeletal assemblages of the 1960s and 1970s focused on *in situ* demographic change and ignored migration as an influencing factor (e.g., Haviland 1967; Rathje and Sabloff 1973). Bioarchaeological research on Maya human skeletons now contributes to understandings of prehispanic Maya health, diet, social change, inequality, migration, mobility, war, violence, interregional interaction, and ritual practice (e.g., Cucina 2015b; Cucina and Tiesler 2005; Scherer 2017; Tiesler and Cucina 2014; White 1999; Whittington and Reed 1997b; Wright 2004, 2006; Wright and White 1996; Wrobel 2014a). While several aspects of human skeletal remains have been used to identify nonlocal individuals in Maya archaeological contexts, such as cranial and dental modifications (e.g., Tiesler 2015), biodistance and isotopic analyses are the most commonly employed.

In terms of migration, biological distance (biodistance) studies have been useful for elucidating general patterns of population level migration within the Maya region and beyond. Biodistance studies of Maya skeletal assemblages typically focus on the metric

and nonmetric characteristics of the dentition because teeth preserve better than bone in tropical areas and cultural practices such as cranial modification can obscure phenotypic expression in the cranium (Scherer 2007; Wrobel 2003). In general, these studies have identified a high degree of biological affinity compared to other Mesoamerican populations indicative of extensive migration within the Maya region that was fairly consistent over time (Aubry 2019; Cucina 2015b; Cucina and Tiesler 2004; Jacobi 1997; Scherer 2007; Wrobel 2003). The analysis of DNA from both modern Maya people and the ancient DNA (aDNA) of Maya skeletal samples are also useful for reconstructing population structure in the past (González-Oliver et al. 2001, 2018; Merriwether et al. 1997).

While genetic studies of Maya skeletal assemblages reveal interesting patterns of population dynamics that can be reconstructed from a general perspective both within and between sites (Austin 1978; Cucina and Tiesler Blos 2004; Cucina et al. 2018; Serafin et al. 2014, 2015; Wrobel and Graham 2015), they can only examine migration at the population level. Although these techniques are not suited for identifying migration at the level of the individual, the understandings of population structure throughout the Maya region and over time provided by biodistances analyses can assist with the interpretation of individual migration offered by isotopic analyses.

However, biological anthropological analyses of Maya skeletal assemblages, including those that utilize isotopic analyses, are challenging for several reasons (see Wrobel 2014b:2-5). For example, the prehispanic Maya did not use formal cemeteries, and instead select individuals were buried within structures that continued to be used by the living, suggesting that decedents were afforded social viability and descendants engaged in ongoing dialogues with their ancestors (McAnany 1995; Gillespie 2001). This selectivity,

however, reduces the number of individuals available for analysis and brings into question the representativeness of Maya skeletal samples (Jackes 2011; Wright and Yoder 2003:44). The posthumous manipulation of bodies by the Maya, including the extraction or introduction of skeletal elements to burial contexts, individual and collective reburial, and the reuse of bones as relics (Tiesler 2007:18; see also McAnany 1995:60; McAnany et al. 1999; Tiesler and Cucina 2007), is also a concern because isotopic analyses cannot differentiate between people who migrated during life and those whose remains were moved following their deaths (Freiwald 2011a:61). This is further complicated by the generally poor preservation of organic material, including human bone, at Maya sites that decreases the amount and quality of material for analysis. With these caveats in mind, the application of isotopic approaches to questions of migration within the Maya region are reviewed below.

2.4.3 Isotopic Approaches to Maya Migration

Despite the challenges associated with analyzing Maya skeletal assemblages, researchers have successfully identified nonlocal individuals at numerous sites from varying time periods using isotopic techniques and have greatly contributed to understandings of migration among the Maya. Strontium and oxygen are the most widely used isotope systems for investigating the movement of both humans and animals in past societies and as illustrated in Figure 2.2, they have been extensively applied in the Maya region (Buikstra et al. 2004; Cucina et al. 2015; Freiwald 2011a, 2011b, 2020; Freiwald and Pugh 2018; Freiwald et al. 2014, 2020; Hoffmeister 2019; Micklin 2015; Miller 2015; Mitchell 2006; Negrete et al. 2020; Novotny 2015; Ortega-Muñoz et al. 2019; Patterson

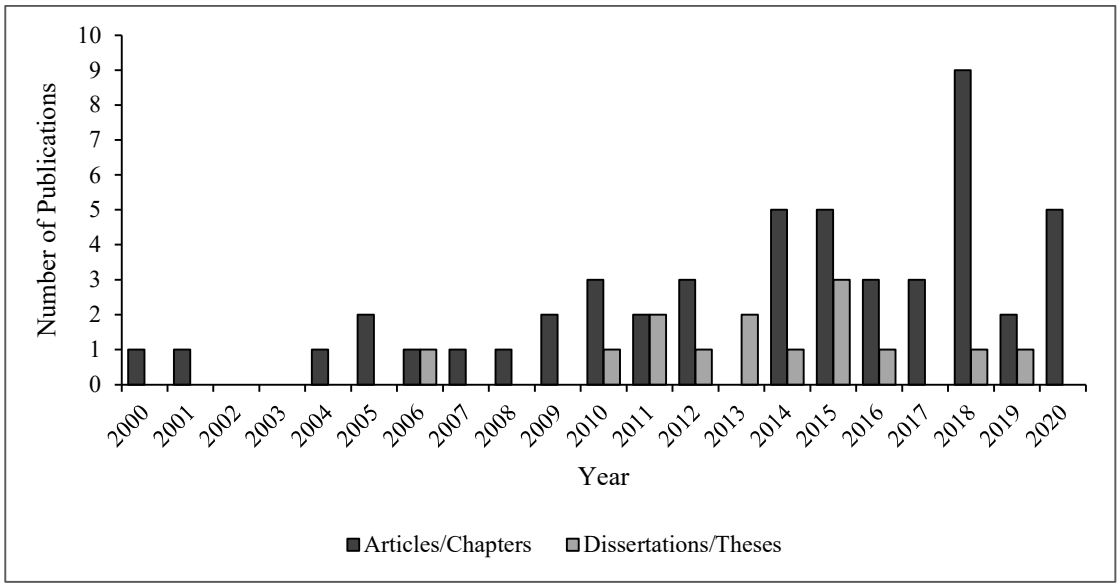

Figure 2.2: Number of studies that utilized strontium and/or stable oxygen isotope analysis to investigate mobility and migration of humans and/or animals at Maya sites over time. Data collected through a Google Scholar™ search starting at the year 2000 using the key words "Maya", "archaeology", "migration", "mobility", "oxygen isotopes", and/or "strontium isotopes". Note that only peer-reviewed articles, chapters in edited volumes, and graduate dissertations and theses were included, and that review articles and studies that analyzed isotope systems other than oxygen and strontium were omitted.

and Freiwald 2016; Price et al. 2006, 2008, 2010, 2013, 2014, 2015, 2018a, 2018b, 2019; Rand 2017; Rand et al. 2020a; Scherer and Wright 2015; Sharpe et al. 2018; Sierra Sosa et al. 2014; Somerville et al. 2016; Sugiyama et al. 2018; Sutinen 2014; Suzuki et al. 2018, 2020; Thornton 2011; Thornton et al. 2016; Tiesler et al. 2010; Trask et al. 2012; White et al. 2000, 2001; Wright 2005a, 2005b, 2012, 2013a; Wright and Bachand 2009; Wright et al. 2010; Wrobel et al. 2014, 2017; Yaeger and Freiwald 2009).

Although isotopically nonlocal individuals were not identified at Actuncan (Micklin 2015) and Actun Uayazba Kab (Wrobel et al. 2017) in Belize, and El Meco in Mexico (Ortega-Muñoz et al. 2019), the remainder of the isotopic studies cited above report a high degree of mobility at Maya sites, where up to 50% of sampled individuals were

identified as nonlocal (Freiwald 2011a, 2011b; Freiwald et al. 2014; Price et al. 2018a, 2018b). Nonlocal individuals at many sites have also been found to have originated from multiple isotopically distinct localities (Freiwald 2011a, 2011b; Freiwald et al. 2014; Miller 2015; Miller Wolf and Freiwald 2018; Negrete et al. 2020; Ortega-Muñoz et al. 2019; Price et al. 2014, 2018a, 2018b, 2019; Somerville et al. 2016; Suzuki et al. 2018, 2020; Wright 2005a, 2012).

Initial isotopic studies assessed the utility of this technique for identifying nonlocal individuals at Maya sites, critiqued aspects of the methodology, such as how to define baseline values, and suggested reasons for discrepancies in the data sets, such as the consumption of imported salt and water from different sources (Buikstra et al. 2004; Price et al. 2007, 2008; Scherer et al. 2015; White et al. 2000, 2001; Wright 2005a, 2005b). Subsequent studies have further investigated these issues and contributed to better understandings of baseline values in the Maya region (Fenner and Wright 2014; Freiwald et al. 2019; Price et al. 2010; Miller Wolf and Freiwald 2018; Scherer et al. 2015). Now that these methods are firmly established, they are regularly integrated into interdisciplinary studies of the impact of migration on Maya culture, as discussed below.

The first isotopic case studies of skeletal collections from Maya sites addressed a long-standing debate in Mesoamerican archaeology: the degree to which Central Mexican-style material culture and epigraphic evidence represents the migration of people from Teotihuacan to Maya sites during the Early Classic period and the nature of this contact (Braswell 2003). Teotihuacan, located in the Valley of Mexico, was the largest city in Mesoamerica and reached its zenith during the Proto- and Early Classic periods. The appearance of material culture from this Central Mexican city (i.e., green obsidian), as well

as the import or emulation of artifacts (i.e., tripod cylindrical vases, shell "goggles") and architecture (i.e., *talud-tablero* platforms) at Maya sites, combined with militaristic symbolism at Teotihuacan itself, led researchers to question the extent of the presence and influence of Teotihuacanos at Maya sites during the Early Classic period (Braswell 2003). Based on the epigraphic evidence from several sites, Stuart (2000) has proposed that Teotihuacan played a direct and disruptive role in the political history of sites in the central Peten, particularly Tikal and Uaxactun, in the Early Classic period, but that this direct contact waned and, following the fall of Teotihuacan, Late Classic rulers across the lowlands appropriated Central Mexican styles and material culture as prestigious or legitimating symbolism and militaristic ideology.

Epigraphic evidence from Tikal, Uaxactun, Bejucal, and Río Azul in the central Peten has been interpreted as some to support "the establishment of a New Order in the central lowlands, with Teotihuacan or its agents subordinating or reconfiguring certain Maya regimes to its liking" (Martin 2020:241; see also Martin and Grube 2008:29-33; Martin 2001:111). Such interpretations of a Central Mexican *Entrada* into the Central Lowlands focus on the documented arrival of a lord called Sivah K'ak' (formerly "Smoking Frog")[5] clothed in Teotihuacan military attire who presided over the installations of kings at those centres, although researchers do suggest it is possible that he was an ethnically Maya general under the auspices of Teotihuacan (Martin and Grube 2008:31; see also Kováč et al. 2019; Stuart 2000). This evidence suggests that a second individual involved in the Entrada was "Spear-Thrower Owl" (Martin and Grube 2008:30), the father of Nun

[5] Mayan names are used for individuals whose glyphs can now be read and English nicknames assigned by epigraphers are used in quotation marks for individuals whose glyphs have not yet been deciphered.

Yax Ayin, the king installed at Tikal in 379 CE. The texts note that Spear-Thrower Owl was made king in 374 CE but not of Tikal. Based on his Central Mexican garb, Stuart (2000:483) speculates that he was the ruler of Teotihuacan, although he recognizes this is not currently substantiated by the evidence. A third individual, K'inich Mo', who appears on a mural at Uaxactun has been interpreted as a Teotihuacan military captain or representative of Sivah K'ak' who aided the ethnically Maya "Sunraiser" in taking control of that site and founding a new dynasty in 378 CE (Kováč et al. 2019). The problem with these interpretations is that all of the event glyphs in the texts come from a limited number of sites in central Petén and are read *hul-iy*, interrupted as "he/she/it arrived" (Stuart 2000:477), meaning there is no direct, unequivocal epigraphic evidence that states these arrivals were associated with military interference at Maya sites.

The isotopic evidence suggests that this "New Order" was installed without the movement of Teotihuacanos, as few individuals from Maya sites have isotopic values consistent with those of Central Mexico (see Chinchilla Mazariegos et al. 2015; Rand et al. 2020a; Wright et al. 2010; see also Chapter 5) and most nonlocal individuals at Maya sites originated from elsewhere in the Maya region (Price et al. 2010; White et al. 2000, 2001; Wright 2005a, 2005b, 2010, 2012; Wright and Bachand 2009). For example, although epigraphic evidence suggests Yax Nuun Ayiin I was born in Teotihuacan because he "arrived" at Tikal to be crowned king in 379 CE, his local first molar enamel $^{87}Sr/^{86}Sr$ value (0.70828) instead indicates he was born and lived near Tikal during childhood (Wright 2005b).

Similarly, material evidence initially suggested that individuals from Teotihuacan invaded Kaminaljuyu (Kidder et al. 1946; Sanders and Michels 1978); however, of the 63

teeth from 24 Early Classic burials analyzed by Wright and colleagues (2010), only the third molar $\delta^{18}O$ (–6.8 ‰) and $^{87}Sr/^{86}Sr$ (0.70492) values of one adult of unknown sex (Tomb A-V-1) are consistent with those of Central Mexico. The isotopic values of the first molar ($\delta^{18}O$ = –4.2 ‰, $^{87}Sr/^{86}Sr$ = 0.70465) and third premolar ($\delta^{18}O$ = –4.5 ‰) from this individual are local, indicating he or she was born in Kaminaljuyu, spent his or her later childhood elsewhere, perhaps in Central Mexico, and returned to the Highland Maya site prior to death (White et al. 2000; Wright et al. 2010).

Finally, Late Classic rulers of Copan recorded how the founder of their dynasty, K'inich Yax K'uk' Mo', arrived at the site in 426 CE and depict him in Teotihuacan regalia; however, a portrait of the dynastic founder commissioned by his son during the Early Classic does not depict him in Central Mexican garb, suggesting his association with Teotihuacan was elaborated upon by later kings to demonstrate their affiliation with Central Mexico (Stuart 2000:500). Other lines of evidence suggest that he instead originated from the central Peten, possibly from Tikal or Caracol, and was ethnically Maya with a political identity rooted in Teotihuacan (Stuart 2007), although the texts that describe him were written centuries after his death. Isotopic analyses of his remains confirm this interpretation whereby the $^{87}Sr/^{86}Sr$ (0.70844) and $\delta^{18}O$ (–3.4 ‰) values of his first molar enamel and show he spent his childhood in the central Peten, moved to another location around aged 11 based on the values of his third molar (0.70736 and –4.0 ‰, respectively), and had moved closer to Copan by adolescence based on the $^{87}Sr/^{86}Sr$ value of his fibula (0.70633; Buikstra et al. 2004; Price et al. 2010).

The lack of isotopically identified individuals from Central Mexico may represent a sampling bias, whereby individuals from Teotihuacan have not been subjected to isotopic

analyses, or that the invading Teotihuacanos chose to install local Maya as their ruling vassals. Regardless, the lack of isotopic evidence for the presence of individuals from Teotihuacan at Maya sites refutes positions that emphasize direct Teotihuacan military imperialism, and instead supports arguments that Teotihuacano impact at many sites was indirect or that the appearance of Central Mexican stylistic traits in the Maya region may instead represent the emulation of Teotihuacano ideology and symbolism by Early Classic Maya rulers and their Late Classic successors to enhance their own power or status (e.g., Price et al. 2010; White et al. 2001; Wright 2005b). Furthermore, it appears that the relationship between individuals from Teotihuacan and the Maya region was reciprocal, multidimensional, and variable across time and space (Estrada-Belli et al. 2017; Marcus 2003).

Early isotopic studies in Maya archaeology also focused on confirming the epigraphic evidence for the origins of other royal individuals at large, intensively studied centres, including Tikal, Copan, and Palenque (Price et al. 2010; Wright 2005a, 2012). Subsequent research now additionally analyzes individuals from smaller hinterland sites and has revealed that migration was not restricted to large Maya centres, but also occurred in rural communities. For example, nearly a quarter of sampled individuals from different sized sites in the Belize Valley relocated at least once during their lives (Freiwald 2011a; also see Freiwald 2011b, 2021; Green 2016; Micklin 2015; Mitchell 2006; Novotny 2015; Rand 2017; Spotts 2013; Wrobel et al. 2014, 2017). As with contemporary migration, most individuals appear to have relocated over short distances, which can be isotopically visible if there is sufficiently diverse geology within one region, such as the Belize Valley and surrounding area, or by sampling multiple isotopes and tissues from the same individual

(Freiwald 2011a; Freiwald et al. 2014; Miller Wolf and Freiwald 2018; Patterson and Freiwald 2016; Price et al. 2018a; Rand 2017).

A major area of research in bioarchaeological isotope studies of Maya migration concerns interregional interaction, although the Maya themselves were diverse and intraregional migration is also an important area of study. Contact between the Maya and other Mesoamerican peoples, particularly from Teotihuacan in Central Mexico, has been extensively investigated in isotopic studies, as discussed above. Researchers are also beginning to examine the integration of non-Maya people from western/central Honduras in the Maya centre of Copan (Miller Wolf and Freiwald 2018; Suzuki et al. 2020). However, the Maya were not ethnically homogenous, and although archaeological discourse often conflates the various peoples who inhabited the Maya region into a single culture group based on similar languages, genetics, and material culture, the people who lived in this area were, and their descendants are, ethnically diverse (Price et al. 2018b:70; Scherer et al. 2018). Furthermore, because ethnicity and identity are social constructs, it is likely that they changed over time and throughout a person's lifetime (Díaz-Andreu and Lucy 2005:2). While it can be challenging to etically reconstruct prehispanic and Colonial Maya ethnicity and identity, and how people in one Maya polity perceived those in another, important insights have been gained through the examination of archaeological evidence (Díaz-Andreu et al. 2005), ethnographic analogy and material culture (Scherer et al. 2018), as well as bioarcheological studies (e.g., Tiesler 2013; Willermet and Cucina 2018).

Recently, isotopic investigations of migration at Maya sites have contributed to reconstructions of the identity of nonlocal individuals. Place of origin is not the only aspect of individual identity, but is one that may be inferred through an interdisciplinary isotopic

approach that considers how the identity of nonlocal individuals was expressed in their funerary contexts, and other aspects of identity and group affiliation such as cranial and dental modifications (Freiwald et al. 2014; Cucina et al. 2015; Green 2016; Novotny 2015; Olsen et al. 2014; Ortega-Muñoz et al. 2019; Price et al. 2014, 2018a, 2018b; Sierra Sosa et al. 2014; Suzuki et al. 2018; Trask et al. 2012).

Another aspect of identity is gender, although bioarchaeological approaches are limited to the identification of biological sex (i.e., males and females; Geller 2008; Walker and Collins Cook 1998). Migratory differences between males and females attributed to relocations for marriage were proposed among the prehispanic Maya based on epigraphic evidence and Colonial exogamy patterns (Martin and Grube 2008; Robinson 1981). At Copan, isotopic analyses found sex-related differences in mobility within specific neighbourhoods and that males and females may have come from different regions (Miller 2015). It also appears that males from western Honduras moved to Pusilha in southern Belize to marry into the royal family (Somerville et al. 2016). However, most isotopic studies to date have found that Maya of both sexes moved to numerous sites in similar proportions (Freiwald 2011a; Miller 2015; Ortega-Muñoz et al. 2019; Price et al. 2018b; Suzuki et al. 2018), confirming that prehispanic Maya post-marital residence preferences were complex, as they were in the Colonial period and are today (Wilk 1988:139-140). The balanced sex ratio may further indicate Maya people moved not as individuals, but in familial groups or possibly as part of larger groups (e.g., lineages) that were unrelated to marriage patterns (Scherer, personal communication, 2021).

Social status, as inferred from mortuary contexts, is another aspect of identity that may be correlated with an individual's nonlocal origin. Despite the early focus on the

movement of elites at major sites, isotopic analyses have confirmed that isotopically identifiable migration also regularly occurred among lower status Maya at many sites (Freiwald 2011a; Mitchell 2006; Price et al. 2008, 2010; Suzuki et al. 2018; Wright 2005a; Wright et al. 2010). It also appears that nonlocal origins may have been an important factor for the inclusion of individuals in sacrificial contexts (Chinchilla Mazariegos et al. 2015; Freiwald et al. 2014; Price et al. 2007, 2019) and as trophy skulls (Price et al. 2018b; Tiesler et al. 2010). Isotopic data also indicate that local elites at Cahal Pech may have emulated nonlocal burial orientations and styles as a means of associating themselves with more powerful centres (Novotny et al. 2018). Conversely, nonlocal individuals buried using local mortuary customs at Xunantunich indicate the social integration of nonlocal individuals into the local community at this site (Freiwald et al. 2014).

Beyond reconstructing the identity of nonlocal individuals, the incorporation of isotopic analyses into interdisciplinary research projects offers the opportunity to broaden conceptual frameworks for explaining past political, economic, and social networks, population dynamics, and site formation processes. While exact places of origin cannot be determined, the general places of origin of nonlocal individuals can be narrowed down and are important for reconstructing the directionality of migration flows. This in turn speaks to the interactions among particular areas throughout the wider Maya area, providing insights into sociopolitical, kin-based, and trade networks (Cucina et al. 2015; Miller 2015; Novotny et al. 2018; Price et al. 2014, 2018a; Sierra Sosa et al. 2014; Somerville et al. 2016). Similarly, the role of migration and other demographic processes in the formation and expansion of sites and changes in sociopolitical networks can be explored by examining when nonlocal individuals were buried (Scherer and Wright 2015; Wright 2012; Suzuki et

al. 2020). The identification of nonlocal animals at Maya sites also provides insights into trade and exchange, economics, and catchment use (Freiwald and Pugh 2018; Sharpe et al. 2018; Sugiyama et al. 2018; Thornton 2011; Thornton et al. 2016; Yaeger and Freiwald 2009).

It should also be noted that most isotope studies in the Maya region have focused on skeletal collections dating to the Classic period, predominantly the Late Classic period. This is largely an artifact of archaeological sampling bias and preservation. However, the isotopic examination of skeletal remains from later time periods, such as those from Colonial period cemeteries, provides important insights into the impact of European colonialism on the movement of resources as well as people of Maya, European, and African descent in Spanish colonies (Freiwald and Pugh 2018; Freiwald et 2020; Price et al. 2006, 2013; Trask 2018).

Finally, the extensive body of isotopic research in the Maya region provides an excellent foundation for the application of novel techniques, such as stable sulfur isotope analyses. Expected variation in the $\delta^{34}S$ values throughout the Maya region appears to complement that of strontium and oxygen isotope systems (Rand and Grimes 2017). Importantly, unlike strontium and oxygen isotopes, which are primarily analyzed from tooth enamel that forms in childhood, sulfur isotope values of bone collagen reflect dietary averages from adolescence until the end of life, depending on the bone and individual physiology in bone turnover rates (Hedges et al. 2007; Matsubayashi and Tayasu 2019; Parfitt 2001). Researchers can therefore identify relocation in the final years of life, a contrast to childhood isotopic values that also can elucidate the number of times individuals moved over their lifetimes and how long they may have resided in a region prior to death.

This is, of course, only possible if the individual migrated from isotopically distinct regions. Regardless, it appears as though sulfur isotope analysis has the potential to contribute to understandings of human movement at Maya sites.

2.5 Chapter 2 Summary

Although mobility is a common aspect of human behaviour, archaeological migration was traditionally uncritically invoked as a post hoc explanation for change in material culture or differences in cranial shape. With their interest in *in situ* development, processualists largely ignored migration as a demographic process, as did many bioarchaeologists of the time (Adams et al. 1978; but see Buikstra 1977). With the advent of postprocessual perspectives, researchers revived migration as an important aspect of past societies but struggled to develop an archaeological proof of migration (Anthony 1990; Burmeister 2000). Theoretical developments are intertwined with available methods and data sets, and the development of isotopic techniques for identifying nonlocal individuals have transformed archaeological understandings of past human migration. For example, isotopic analyses revealed that elite individuals interred at Maya sites with Teotihuacan-style material culture were from the Maya region, which changed archaeological understandings of the nature of interaction between these two regions of Mesoamerica (Price et al. 2010; White et al. 2001; Wright 2005b).

Every analytical technique is, however, accompanied by assumptions and limitations that must be acknowledged. The minimum definition of isotopically identifiable migration as occurring when individuals moved from isotopically distinct regions at least once during their lives acknowledges both the strengths and limitations of this technique

for understanding past migrations and can be modified to accommodate specific archaeological contexts. Despite the challenges associated with bioarchaeological studies of human remains from Maya sites (Wrobel 2014b), the integration of isotopic analyses into interdisciplinary research can not only reconstruct individual life histories and identities, but also contribute to broader understandings of sociopolitical organization, interaction, and change over time (Freiwald et al. 2014; Cucina et al. 2015; Ortega-Muñoz et al. 2019; Price et al. 2014, 2018a, 2018b; Sierra Sosa et al. 2014; Suzuki et al. 2018; Trask et al. 2012). Building on this theoretical framework, the utility of stable sulfur isotope analyses for identifying the movement of people and resource acquisition in archaeological studies of both migration and subsistence practices among the Maya is explored in the following chapters.

CHAPTER 3

A MULTI-ISOTOPIC (δ^{34}S, δ^{13}C, AND δ^{15}N) FAUNAL BASELINE FOR MAYA SUBSISTENCE AND MIGRATION STUDIES[6]

Stable sulfur isotope (δ^{34}S) analysis is a useful technique for studying differential consumption of terrestrial, marine, and freshwater protein, as well as detecting nonlocal humans and animals in archaeological contexts (Nehlich 2015; Rand and Nehlich 2018). This is possible because sulfur isotope values in bone collagen reflect those of the environment from which dietary protein is derived (i.e., terrestrial, freshwater, or marine) and are influenced by the underlying geology, atmospheric deposition, and biological processes (see Nehlich 2015). Most archaeological applications of sulfur isotope analysis, however, have focused on temperate regions in Europe and Asia (Cheung et al. 2017a; Craig et al. 2006; Curto et al. 2019; Fornander et al. 2008; Linderholm et al. 2008b; Madgwick et al. 2019a; Nehlich et al. 2010, 2011, 2012; Privat et al. 2007; Richards et al. 2001) and tropical islands in Oceania and the Caribbean (Kinaston et al. 2014; Leach et al. 1996; Sparks and Crowley 2018; Stantis et al. 2015).

[6] A version of this chapter has been published in the *Journal of Archaeological Science: Reports* co-authored with Dr. Carolyn Freiwald and Dr. Vaughan Grimes (Rand et al. 2021a). CF and VG provided samples, resources, supervision, and comments on previous drafts of this chapter. However, as the principal author, AR was responsible for the research design, acquiring samples, preparing and weighing the samples for analysis, analyzing and interpreting the results, drafting the original manuscript, editing various drafts, and submitting the final manuscript for publication and inclusion in this dissertation.

In Mesoamerica, prehispanic Maya subsistence has been extensively studied using multiple techniques, including stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope analysis (Somerville et al. 2013; Tykot 2002; White 1999; White et al. 2006). Human migration and animal trade in this region have been similarly investigated through multidisciplinary approaches that include strontium ($^{87}Sr/^{86}Sr$) and stable oxygen ($\delta^{18}O$) isotope analysis (Cucina et al. 2015; Price et al. 2010; Thornton 2011; Wright et al. 2010). These studies provide the basis for evaluating the utility of stable sulfur isotope analysis in Maya archaeology. Indeed, preliminary stable sulfur isotope analyses of Maya diet and mobility show promising results (Awe et al. 2017; Green 2016; Rand and Grimes 2017; Rand et al. 2020a), but with only a small number of human and faunal baseline samples, more research is needed.

This study assessed whether the differing $\delta^{34}S$ values of the heterogeneous environments of the Maya region of Central America can address archaeological questions of subsistence, movement, and animal exchange in tropical coastal and continental contexts. The expected variability in environmental $\delta^{34}S$ values throughout the Maya region is hypothesized using an extensive literature review. The diets of 148 fauna specimens from 13 Maya sites are assessed by comparing their $\delta^{13}C$ and $\delta^{15}N$ values to other isotopic studies of Maya faunal assemblages. The faunal $\delta^{34}S$ values are compared to the hypothesized environmental variation in the Eastern and Northern Lowlands, creating the first extensive $\delta^{34}S$ baseline in Mesoamerica and a tropical continent setting more generally. The results show that multi-isotopic studies that incorporate stable sulfur isotope analysis can further contribute to archaeological understandings of Maya subsistence and the movement of both humans and animals at multiple sites.

3.1 Principles of Stable Isotope Analysis

Carbon ($^{12}C/^{13}C$), nitrogen ($^{14}N/^{15}N$), and sulfur ($^{32}S/^{34}S$) isotope analysis measures the ratio of the two most abundant stable isotopes in a sample material (e.g., bone collagen) relative to their ratio in a standard reference material (Vienna Peedee Belemnite (VPDB), atmospheric N_2 (AIR), and Vienna Cañon Diablo Troilite (VCDT), respectively; Böhlke et al. 1993; Coplen and Krouse 1998; Coplen et al. 2006) and the results are reported using the delta (δ) notation in per mil (‰) units. The $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values of bone collagen primarily reflect the isotopic composition of dietary protein consumed from adolescence to the end of life, depending on which bone was sampled and individual physiological turnover rates (Ambrose and Norr 1993; Hedges et al. 2007; Howland et al. 2003; Jim et al. 2004; Matsubayashi and Tayasu 2019; Richards et al. 2003; Webb et al. 2017) and each reveals different aspects of diet, as described below.

Bone collagen $\delta^{13}C$ values provide information on the types of plants and animal proteins a population consumed. Most plants use the C_3 photosynthetic pathway and have a modern global average $\delta^{13}C$ value of a –26.5 ‰, whereas C_4 plants such as maize from Mesoamerican archaeological sites range from –12.5 ‰ to –9.0 ‰ (O'Leary 1988; Smith and Epstein 1971; Tieszen and Fagre 1993; Warinner et al. 2013). Although some plants in this region utilize the Crassulacean acid metabolism (CAM) photosynthetic pathway and have intermediate $\delta^{13}C$ values, it is unlikely they were consumed in significant quantities by the Maya (Powis et al. 1999; White 2005). Carbon isotope ratios minimally increase at each level of the food chain so that consumer bone collagen $\delta^{13}C$ values indicate whether dietary protein was derived from C_3 or C_4 plants (Ambrose and Norr 1993; Bocherens and Drucker 2003; Schoeninger and DeNiro 1984).

Most wild terrestrial game species consumed by the Maya, including white-tailed deer (*Odocoileus virginianus*), brocket deer (*Mazama* sp.), peccary (Tayassuidae), tapir (*Tapirus bairdii*), lowland paca (*Cuniculus paca*), agouti (*Dasyprocta* sp.), turkeys (*Meleagris* sp.), and nine-banded armadillo (*Dasypus novemcinctus*), as well as edible freshwater species including various turtles (*Trachemys venusta* and other Emydidae, Kinosternidae), mussels (*Nephronaias* sp.), *jute* snails (*Pachychilus* ssp.), and to a lesser extent crocodiles (Crocodylidae), exhibit low δ^{13}C values (~ –22 to –19 ‰) consistent with diets from ecosystems based on C_3 plants (Tykot et al. 1996; White and Schwarcz 1989; Williams et al. 2009; Wright 2006). However, some archaeological deer and peccary as well as domesticated dogs (*Canis lupus familiaris*) and turkeys that were consumed by the Maya have more elevated δ^{13}C values between –17.5 and –8.2 ‰, indicating these animals consumed maize (Sharpe et al. 2018; Thornton et al. 2016; White et al. 2001).

Archaeological evidence demonstrates that marine taxa, such as sea turtles (e.g., *Caretta caretta*), various fish and shellfish, and to a lesser extent manatee (*Trichechus manatus*) were consumed at coastal Maya sites (McKillop 1985; Williams et al. 2009). Although marine animals, particularly mollusks, were traded inland, they were likely imported as artifacts signifying status rather than as sources of food (Sharpe and Emery 2015). Marine resources consumed by the Maya typically exhibit δ^{13}C values above –10 ‰ (Keegan and DeNiro 1988; Tykot et al. 1996; van der Merwe et al. 2002; Williams et al. 2009). Because marine-based diets have δ^{13}C values that overlap those of maize-based diets in the Maya region, additional isotope systems are required to differentiate between the two.

Stable nitrogen isotope values increase between 3 and 6 ‰ with each trophic level

in the food chain so that the δ^{15}N values of herbivores are lower than those of carnivores (Delwiche and Steyn 1970; Hedges and Reynard 2007; O'Connell et al. 2012; Schoeninger and DeNiro 1984). The δ^{15}N values of bone may also be influenced by environmental factors including climate, precipitation, aridity, and soil nitrates (Ambrose 1991, 2000), as well as physiological conditions such as nutritional stress and pregnancy (Fuller et al. 2004, 2005). Bone δ^{15}N values may also differ between archaeological human populations with marine and terrestrial diets (Schoeninger and DeNiro 1984; Schoeninger et al. 1983) because aquatic food webs comprise between four and six trophic levels, whereas terrestrial food chains generally contain only three (Hairston and Hairston 1993). Humans typically consume terrestrial herbivores that occupy the second trophic level and marine fauna that fall within the third to fifth trophic levels (Bonhommeau et al. 2013), so that terrestrial-based human diets exhibit lower δ^{15}N values than those based on marine protein from higher trophic level fauna.

However, the δ^{15}N values of higher trophic level marine animals typically consumed by the Maya (+7.7 ± 3.2‰, n = 44; Keegan and DeNiro 1988; Williams et al. 2009) are lower than those of marine species elsewhere in the world (e.g., average δ^{15}N of +11.8 ‰ in Belgium; Fuller et al. 2012). As a result, the δ^{15}N values of marine fauna in this region overlap those of terrestrial game animals consumed by the Maya, such as white-tailed deer and peccary (+4 to +6 ‰), as well as higher values (~+10 ‰) reported from omnivorous domesticated dogs and turkeys in Maya faunal assemblages (Sharpe et al. 2018; Thornton et al. 2016; Tykot et al. 1996; van der Merwe et al. 2002; Wright 2006). The Maya who consumed higher trophic level marine animals may therefore exhibit both δ^{13}C and δ^{15}N values that are indistinguishable from those produced by a terrestrial maize-

based diet. Stable sulfur isotope analysis has successfully been used to differentiate the consumption of marine, terrestrial, and freshwater resources in archaeological contexts in Europe, Asia, Oceania, and the Caribbean (Craig et al. 2006; Curto et al. 2019; Fornander et al. 2008; Kinaston et al. 2014; Leach et al. 1996; Linderholm et al. 2008b; Madgwick et al. 2019a; Nehlich et al. 2010, 2011, 2012; Privat et al. 2007; Richards et al. 2001; Sparks and Crowley 2018; Stantis et al. 2015), and may also be useful for identifying dietary protein sources in tropical continental contexts such as the Maya region.

Plants assimilate most of their sulfur from inorganic sulfate (SO_4^{2-}) derived from the underlying geology or dissolved in aquatic environments (Monaghan et al. 1999; Noji and Saito 2003; Trust and Fry 1992), although wet (i.e., sea spray) and dry deposition (i.e., SO_2 gas) as well as microbial activity can also contribute sulfur to plant tissues (Agrawal 2003; Jørgensen et al. 2019; Krouse and Grinenko 1991). Plants convert assimilated sulfate into various sulfur-containing molecules including methionine ($C_5H_{11}NO_2S$) with minimal fractionation[7] so that the $\delta^{34}S$ values of plant tissues reflect those of environmental sulfate (Peterson et al. 1985; Tanz and Schmidt 2010). Methionine is an essential amino acid and the only one to contain sulfur in bone collagen (Nehlich and Richards 2009). Animals cannot synthesize methionine and must obtain it from dietary protein that is ultimately derived from plants at the base of the food chain (Brosnan and Brosnan 2006; Ingenbleek 2006; Tanz and Schmidt 2010). The trophic level fractionation associated with $\delta^{34}S$ values is considered negligible (+0.5 ± 2.4 ‰; Nehlich 2015; but see Webb et al. 2017) so that the bone collagen values of carnivores are indistinguishable from those of their prey (Krajcarz

[7] The heavier and lighter isotopes of an element react differently during chemical reactions due to mass differences, which causes the isotopic compositions of reactants and products to differ (Fry 2006:12).

et al. 2019).

Because the $\delta^{34}S$ values of bone collagen methionine reflect those of dietary protein derived from plants at the base of the food chain, they will be unaffected by biologically unavailable sulfur inputs from drinking water or food preparation techniques utilized by humans, such as the processing of maize with lime (i.e., nixtamalization) or the addition of salt. Nixtamalization does, however, double the amount of digestible methionine available from maize (Ellwood et al. 2013; Katz et al. 1974), meaning that a greater amount of sulfur in human bone collagen may be derived from lime-processed maize relative to animal protein, which otherwise would be equal (Young and Pellet 1994). This is unlikely to influence the results of the current study, as most sampled archaeological faunal species are unlikely to have consumed lime-processed maize. However, studies of human $\delta^{34}S$ values in cultures where nixtamalization was a common food processing technique would need to take this into consideration.

3.2 Expected Variability of Environmental $\delta^{34}S$ Values in the Maya Region

To interpret the $\delta^{34}S$ values of archaeological bone collagen samples, it is necessary to understand the expected values of various environments in the region of study (Nehlich 2015). As with strontium isotope ($^{87}Sr/^{86}Sr$) values, environmental $\delta^{34}S$ values are largely influenced by the type and age of the underlying geology (Krouse et al. 1991). Therefore, the distinct geologic zones of the Maya region used to predict strontium isotope variability (e.g., Hodell et al. 2004) are useful for predictions of the variability of environmental $\delta^{34}S$ values. However, distance from the coast and microbial activity also impact $\delta^{34}S$ values (Jørgensen et al. 2019; Wadleigh et al. 1996). Drawing on sulfur isotope literature from

various disciplines, the expected variability of δ^{34}S values in the Northern and Southern Lowlands, Motagua Valley, Maya Mountains, Highlands, and coastal areas of the Maya region are hypothesized below and summarized in Figure 3.1.

Modern seawater represents a well-mixed sulfur reservoir with an average worldwide dissolved sulfate δ^{34}S value of +21 ‰ (Böttcher et al. 2007; Rees et al. 1978). Planktonic algae, seaweeds, and other modern marine plants generally have δ^{34}S values (+17 to +21 ‰) similar to seawater sulfate (Peterson and Fry 1987), and controlled feeding experiments demonstrate that their δ^{34}S values are incorporated into the tissues of marine consumers with similarly little fractionation (±1 ‰; Barnes and Jennings 2007; Kanaya et al. 2008; McCutchan et al. 2003). Based on the analysis of modern and archaeological faunal remains, Nehlich and Richards (2009) suggest that offshore marine fish and mammals such as whales and seals as well as humans and animals that live in coastal regions or consume large quantities of seafood will have δ^{34}S values that range from +14 to +19 ‰ (see also Fornander et al. 2008; Peterson et al. 1986).

The δ^{34}S values of coastal marine animals may, however, be lower than those that live in the open ocean due to the input of freshwater in coastal areas (Böttcher et al. 2007; Yamanaka et al. 2000; see discussion below) and microbial dissimilatory sulfate reduction (DSR; Canfield 2001; Jørgensen et al. 2019). DSR is the process by which microbes reduce sulfate and produce sulfide with δ^{34}S values between +3 and –50 ‰ (Thode 1991). DSR occurs in the anaerobic sediments of not only mangrove forests and mud-bottom habitats, both of which are common along the coast of Belize (High 1975), but also in *cenotes* (sinkholes), marshes, and rivers (Böttcher et al. 2007; Fry et al. 1982; Kanaya et al. 2008; Socki et al. 2002; Mizota et al. 1999; Yamanaka et al. 2000). Some flood adapted plants,

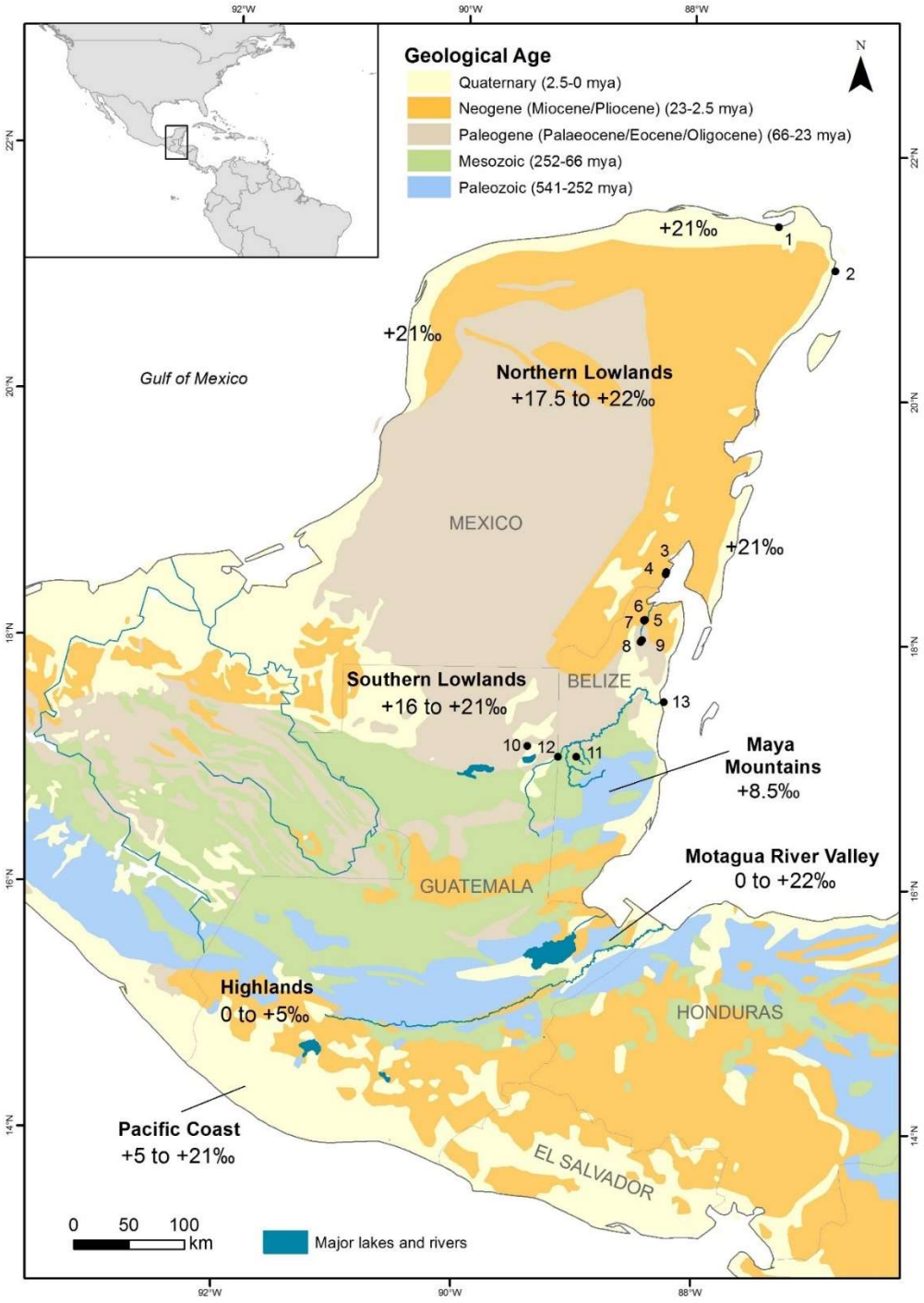

Figure 3.1: Geological map of the Maya region wherein colours represent the age of the underlying geology and location of major lakes and rivers. The hypothesized $\delta^{34}S$ values for different subregions discussed in the text are also indicated, as are the locations of the sites included in this study: (1) Vista Alegre, (2) San Miguelito, (3) Oxtankah, (4) Ichpaatun, (5) Caye Muerto, (6) Chanlacan, (7) Caye Coco, (8) Laguna de On Island, (9) Laguna de On Shore, (10) Nakum, (11) Pacbitun, (12) Xunantunich, and (13) Moho Cay. Map created by Bryn Trapper based on the Geological Map of North America 2005 (1:5,000,000) (Garrity and Soller 2009).

including several species of grasses (e.g., *Spartina* sp.) and mangroves (e.g., *Rhizophora* sp.), can assimilate sulfide-derived sulfur into their tissues, although it is toxic to most plants that instead assimilate sulfate (Lamers et al. 2013). Most sulfide produced through DSR is, however, reoxidized into sulfate with minimal fractionation (Jørgensen et al. 2019), and modern experiments show that plants in anoxic aquatic environments can exhibit $\delta^{34}S$ values that are low relative to dissolved marine sulfate (+21 ‰; Böttcher et al. 2007; Rees et al. 1978) that are subsequently passed on to their consumers (Fry et al. 1982; Holmer and Hasler Sheetal 2014; Mizota et al. 1999; Oakes and Connolly 2004; Peterson et al. 1986; Yamanaka et al. 2000).

Over the oceans, marine sulfur from sea salt and dimethyl sulfide (C_2H_6S) with $\delta^{34}S$ values near those of oceanic sulfate (~+21 ‰) is incorporated into the atmosphere (Amrani et al. 2013; Gravenhorst 1978; Nielsen 1974). The analysis of modern aerosols and peat in coastal areas show that the sea spray effect caused by atmospheric circulation deposits sulfur with elevated $\delta^{34}S$ values in soils up to 30 km inland (Coulson et al. 2005; McArdle et al. 1998; Wadleigh et al. 1994). This makes it difficult to differentiate between the consumption of marine resources and terrestrial diets in coastal regions using $\delta^{34}S$ values alone (Guiry and Szpak 2020). Local climatic factors, such as seasonality, prevailing wind directions, precipitation, and topography (e.g., the presence of mountains, plains, or watersheds) also influence the impact of sea spray $\delta^{34}S$ values on those of inland environments (Bottrell et al. 2000; Sparks et al. 2019; Thode 1991; Wadleigh et al. 1994, 1996; Wakshal and Nielsen 1982).

Atmospheric circulation in the Maya region is dominated by northeasterly winds (Barlow et al. 1998) that carry air masses originating over the Caribbean Sea west across

the Yucatan Peninsula. Air masses originating above the Pacific Ocean travel east and are forced to ascend the Highlands, which are comprised of cordilleras situated parallel to the Pacific Coast. In this mountainous region, rainfall is quickly fed into stream systems where runoff is high (Bethune et al. 2007), although these air masses may reach the Southern Lowlands during the dry season when the wind patterns reverse (Lachniet and Patterson 2009; Tankersley et al. 2016). While sea spray deposits sulfur with elevated δ^{34}S values near +21 ‰ in coastal areas (Coulson et al. 2005; McArdle et al. 1998; Wadleigh et al. 1994), studies of modern aerosols, precipitation, soils, and vegetation also show that atmospheric δ^{34}S values decrease as air masses move inland and rise in elevation, thus contributing sulfur with lower δ^{34}S values (+2 ‰ to +16 ‰) to inland soils and freshwater catchments (Bern et al. 2015; Wadleigh et al. 1994, 1996; Wakshal and Nielsen 1982).

In contrast, the gaseous sulfur emitted from volcanoes has δ^{34}S values around 0‰ (Bottrell and Newton 2006; Holser and Kaplan 1966:94; Nielsen et al. 1991:124), although the average δ^{34}S value of total volcanic sulfur, including ash particles, is approximately +5‰ (Nielsen et al. 1991:125). If an eruption is particularly volatile, various geological strata with differing δ^{34}S values may be pulverized and added to the atmosphere (Nielsen et al. 1991:121). Most volcanic activity in the Highlands has, however, consisted of relatively non-explosive eruptions (van Wyk de Vries et al. 2007) and the primary volcanic contribution of sulfur to the atmosphere in this region is likely in gaseous form. This gaseous volcanic sulfur with δ^{34}S values near 0 ‰ is then deposited in the environment as dry fall or in precipitation, which may extend north into the Southern Lowlands (Tankersley et al. 2016).

However, in humid climates such as those throughout much of the Maya region, the

δ^{34}S values of the underlying geology overwhelms those from atmospheric inputs in inland environments (Sharp 2007:263). The heterogeneous geology of the Maya region should also exhibit different environmental δ^{34}S values (Bundschuh et al. 2007). For example, volcanic rocks typically have δ^{34}S values between 0 ‰ and +5 ‰ (Holser and Kaplan 1966; Labidi et al. 2013), and sulfur with similar values is hypothesized to occur in the volcanic-derived soils of the Highlands, which are deposited down slope into Pacific Coast soils through erosion (van Wyk de Vries et al. 2007). Because the Pacific Coast should also be influenced by sea spray, environmental δ^{34}S values in this subregion are hypothesized to be intermediate between those of marine- and volcanic-derived sulfur (+5 to +21 ‰; Fig. 3.1).

The Maya lowlands are characterized by a karst limestone geology that formed during the evaporation of prehistoric seas (Day 2007), and the δ^{34}S values of the Yucatan Peninsula should decrease from north to south with the increasing age of the underlying limestone (Fig. 3.1). Because the δ^{34}S values of oceanic sulfate fluctuated over time (Bottrell and Newton 2006; Claypool et al. 1980), the δ^{34}S values from limestone that dates to the Mesozoic (252–66 mya; +16 to +21 ‰) in the south should exhibit lower values than those of the Paleogene/Neogene (66–2.5 mya; +17.5 to +22 ‰) farther north. The Quaternary limestones (2.5–0 mya) that line much of the Yucatan coast formed most recently and should have δ^{34}S values near +22 ‰ (Bottrell and Newton 2006; Claypool et al. 1980).

The Motagua Valley of eastern Guatemala is characterized by diverse geology, including volcanic, sedimentary, intrusive, and metamorphic lithologies (Reed et al. 2005). This diversity is hypothesized to contribute variable δ^{34}S values between 0 and +21 ‰ to

terrestrial soils in this subregion. This area is also crossed by the Motagua and Polochic Rivers that drain the interior Highlands and flow east to the Caribbean (Marshall 2007), which may deposit dissolved volcanic sulfate with low δ^{34}S values from the Highlands into the Motagua Valley region.

The Maya Mountains of southwestern Belize and northern Guatemala are a fault-bounded highland with diverse lithology consisting of late Paleozoic sedimentary and volcanic rock (Alvarado et al. 2007; Marshall 2007). Most of this lithology should have a narrow range of δ^{34}S values near 0 ‰ (Thode 1991), and preliminary results from human bone collagen from the Mountain Pine Ridge subregion are around +8.5 ‰ (Ebert et al. under review). However, deposits rich in gypsum (Alvarado and Mota 2007) should exhibit higher values (δ^{34}S = +20 ‰), as will the Vaca Plateau due to the underlying Mesozoic limestone that characterizes the geology within this subarea of the Maya Mountains.

In the Northern Lowlands, cenotes provide access to the underground karst aquifer of freshwater overlying seawater (Perry et al. 2002). The rivers and lakes flowing through limestones in karst environments elsewhere are characterized by high sulfate concentrations with elevated δ^{34}S values (Thode 1991). However, DSR in the anaerobic sediments of cenotes produces sulfide with much lower δ^{34}S values (–34.0 to –2.5 ‰; Socki et al. 2002). Thus, plants in the Northern Lowlands that rely on water from cenotes should exhibit δ^{34}S values lower than those of seawater sulfate (+21 ‰; Böttcher et al. 2007; Rees et al. 1978) due to the influence of DSR in these environments. Aquatic plants in the surface lakes and rivers that dissect the Southern Lowlands are also hypothesized to have δ^{34}S values distinguishably lower than that of modern seawater due to various sulfur inputs. Although rivers that flow through karst landscapes typically acquire higher δ^{34}S values

from sulfate minerals such as gypsum (Cortecci et al. 2002), it is unclear how much sulfate from limestone contributes to freshwater ecosystems in the Maya region (Hu et al. 2005; Williams et al. 1960; Williams and Steinbergs 1962). Major river system catchments in the Southern Lowlands also originate from precipitation with lower $\delta^{34}S$ values deposited in the Highlands or Maya Mountains, regions with underlying geologies that should also exhibit lower $\delta^{34}S$ values. Finally, DSR may also contribute sulfide with lower $\delta^{34}S$ values to anaerobic freshwater environments such as lagoons and cenotes. As a result of the accumulation of sulfur from various sources, not only will rivers exhibit variable $\delta^{34}S$ values along their lengths (Hitchon and Krouse 1972; Longinelli and Cortecci 1970; Peterson et al. 1985; Trembaczowski and Halas 1992), but estuaries will also deposit freshwater with lower $\delta^{34}S$ values into coastal waters (Böttcher et al. 2007).

In this study, archaeological faunal specimens from Maya sites in the Northern Lowlands and the Eastern lowland subregion of the Southern Lowlands were sampled to test the hypothesized variability of sulfur isotope values in this part of the Maya region. Similar studies of the variability of strontium, lead, and stable oxygen isotope ratios throughout the Maya region have analyzed modern geological, water, plant, and animal samples (Freiwald 2011a; Hodell et al. 2004; Lachniet and Patterson 2009; Miller Wolf and Freiwald 2018; Price et al. 2008, 2015; Sharpe et al. 2016; Suzuki et al. 2015; Wassenaar et al. 2008). However, due to contamination from the recent burning of fossil fuels, modern analogues are inappropriate for the evaluation of bioavailable $\delta^{34}S$ values in archaeological settings (Richards et al. 2001; Trust and Fry 1992). Furthermore, although fertilizers are known to influence $\delta^{34}S$ values (Gröcke et al. 2020; Hosono et al. 2007; Mizota and Sasaki 1996; Szpak et al. 2019), the extent to which the prehispanic or Colonial

period Maya used this agricultural technique requires further study (but see Fedick and Morrison 2004; Morrison and Cózatl-Manzano 2003). Zooarchaeological and isotopic analyses also show that although the Maya exchanged animals over varying distances, they primarily consumed locally available animals (Götz 2008; Jiménez Cano and Sierra Sosa 2015; Rand et al. 2020a; Thornton 2011; Yaeger and Freiwald 2009). Thus, the δ^{34}S values of Maya archaeological faunal assemblages should reflect those of locally bioavailable sources of sulfur and demonstrate the variability of environmental δ^{34}S values throughout the Maya region.

3.3 Materials and Methods

The stable carbon, nitrogen, and sulfur isotopes of 148 archaeological bone samples from 13 sites were analyzed, and although 48 additional samples were prepared, they were excluded from this study due to poor preservation, diagenesis, or insufficient collagen (see Results for details). The sites primarily dated to the Classic (250–900/1100 CE), Postclassic (900/1100–1500 CE), or Colonial (after 1500 CE) periods, although specimens from various time periods were sampled from each site. The sample mainly included terrestrial species, which comprise the majority of most Maya faunal assemblages (Emery 2004a). In all, the faunal specimens include 116 terrestrial, 25 freshwater, and 7 marine taxa, including 66 artiodactyls (deer and peccary), 30 medium mammals (agouti, paca, armadillo, opossum, and rabbit), 5 dogs, 13 turkeys, 21 turtles (including 4 sea turtles), 4 crocodiles, 4 birds, and less common prey species such as a manatee, marine mammal, and marine fish (snapper) and carnivores such as a felid and weasel (see Appendix D for detail). Whenever possible, well-preserved specimens identified to the genus or species level without

evidence of cooking or burning were selected for analysis. Although a number of specimens were identified to the family level or higher, this should not have a significant impact on the results as the general habitats used by these taxa (i.e., terrestrial, freshwater, or marine) can still be inferred.

Samples were cleaned, prepared, and analyzed using methods described in detail elsewhere (Rand et al. 2020a; see also Appendix A). Collagen was extracted using a modified Longin (1971) method whereby samples demineralized in hydrochloric acid (HCl) were treated with sodium hydroxide (NaOH) and hydrolysed, ultrafiltered, and lyophilized prior to analysis (Honch et al. 2006; Nehlich and Richards 2009; Szpak et al. 2017b). Although ultrafiltration is not necessary for the preparation of bulk bone collagen samples for stable carbon and nitrogen isotope analysis (Jørkov et al. 2007), it was used in this study to remove exogenous sulfur and retain well preserved collagen for sulfur isotope analysis (Nehlich and Richards 2009; Privat et al. 2007). Additionally, fish specimens were delipidized in 2:1 chloroform:methanol (Guiry et al. 2016; Miller et al. 2010), because lipids present in bone collagen systematically decrease collagen $\delta^{13}C$ values by 1.6 ‰ (Guiry et al. 2016) and fish bone contains a higher proportion of lipids than mammalian bone (Szpak 2011; Toppe et al. 2007). To the best of my knowledge, no study has yet examined the influence of lipid extraction on $\delta^{34}S$ values.

The samples were sent to three laboratories for analysis. Pestle et al. (2014) found that interlaboratory $\delta^{13}C$ and $\delta^{15}N$ values are generally comparable, although this depends on the laboratory. To date, no study has systematically examined the interlaboratory variability of $\delta^{34}S$ values from archaeological bone collagen, but preliminary evidence in Appendix B indicates the results from labs with similar analytical procedures are

comparable. Analytical uncertainty associated with each isotope system and laboratory was calculated using the method proposed by Szpak et al. (2017a) and is detailed in Appendix C. The carbon and nitrogen isotope analyses of the samples from Pacbitun, Moho Cay, Laguna de On Island and Shore sites, Caye Coco, and Chanlacan were conducted by CREAIT's Stable Isotope Laboratory at Memorial University, with a standard uncertainty of ±0.28 ‰ for δ^{13}C and ±0.24 ‰ for δ^{15}N (Appendix C). The carbon and nitrogen isotopes of the Vista Alegre, Oxtankah, Ichpaatun, San Miguelito, and Xunantunich samples were analyzed by the Ján Veizer Stable Isotope Laboratory at the University of Ottawa with an analytical uncertainty of ±0.11 ‰ for δ^{13}C and ±0.08 ‰ for δ^{15}N (Appendix C). The sulfur isotopes of all but two samples were analyzed by the Stable Isotope Laboratory of the Department of Earth and Planetary Sciences at the University of Tennessee. Although standard uncertainty could not be calculated following Szpak et al. (2017a), analytical precision was ±1.00 ‰ for δ^{34}S (Appendix C). Finally, the sulfur isotopes of two samples from Xunantunich were analyzed by the Ján Veizer SIL Stable Isotope Laboratory at the University of Ottawa with a standard uncertainty of ±0.32 ‰ (Appendix C).

Statistical analyses were performed in SPSS version 25 for Windows (IBM®). The distribution of the data was tested for normality using the Shapiro-Wilk test prior to calculating comparative statistics. Small and highly skewed data sets such as those common in archaeological isotope studies are best evaluated using robust, nonparametric statistical techniques (Lightfoot and O'Connell 2016; Pearson and Grove 2013). The interquartile range (IQR) method was therefore used to identify nonlocal individuals as those with statistically outlying δ^{34}S values that fell beyond the IQR multiplied by 1.5 subtracted from the first quartile and added to the third, and extreme outliers fell beyond the IQR multiplied

by 3 subtracted from the first quartile and added to the third (Tukey 1977). Nonlocal individuals are assumed to have originated from an isotopically distinct region, so their $\delta^{34}S$ values were excluded from the calculation of local $\delta^{34}S$ ranges for each site, as has been suggested elsewhere for $^{87}Sr/^{86}Sr$ values (Blank et al. 2018; Pacheco-Forés et al. 2020; Price et al. 2002). Differences in the isotopic values between two groups (e.g., sites, taxa) were evaluated using the Student's *t*-test for normally distributed data and the Mann-Whitney *U* test for nonparametric data and for data sets with less than eight samples (Pearson and Grove 2013). Due to the small sample sizes and nonparametric distribution of data, differences among the isotopic values of three or more groups were evaluated using Kruskal-Wallis *H* tests, and the significances of the pairwise comparisons were automatically adjusted by the Bonferroni correction for multiple tests in SPSS. The results of all tests were deemed to be statistically significant when $p < 0.05$ (see Appendix A for details).

3.4 Results

A total of 148 samples from the original 196 that were prepared for analysis produced sufficient collagen for stable sulfur, carbon, and nitrogen isotope analysis. Of the 48 samples excluded from this study, 15 did not produce collagen, 25 did not produce sufficient collagen for sulfur isotope analysis, and 8 had more than one diagenetic indicator that fell beyond acceptable parameters (Ambrose 1990; Nehlich and Richards 2009; Rand et al. 2015a; van Klinken 1999) and so were excluded from the following interpretations of the results.

3.4.1 Stable Carbon and Nitrogen Isotope Analysis

The $\delta^{13}C$ values ranged from –27.1 to –2.6 ‰ and the $\delta^{15}N$ values ranged from +1.5 to +12.4 ‰ (Appendix D; Table 3.1; Fig. 3.2), complementing existing studies of fauna in the Maya region that show values for common food species used by the Maya as well as other consumers in the food web (i.e., carnivores) (see Gerry 1993; Gerry and Krueger 1997; Tykot et al. 1996; van der Merwe et al. 2002; White and Schwarcz 1989; White et al. 1993; Williams et al. 2009; Wright 2006). As seen in Figure 3.2, most terrestrial herbivores, omnivores, insectivores, and carnivores, as well as freshwater turtles and crocodiles, consumed C_3-based protein as indicated by their low $\delta^{13}C$ values. A brocket deer from Vista Alegre and a paca from Pacbitun had more elevated $\delta^{13}C$ values (–10.7 ‰ and –12.2 ‰, respectively; Fig. 3.2) that fell beyond the range of the other terrestrial herbivores in this study, suggesting these animals consumed maize, perhaps through browsing in maize fields (milpas). Like the wild game animals, some domesticated dogs and turkey species also had predominantly C_3 diets, but most Postclassic turkeys accessed C_4 foods and may have been foddered (e.g., Thornton et al. 2016). Postclassic/Colonial dogs show both C_3 and C_4 diets, depending on the site. Some wild game, such as the wetland dwelling limpkin (*Aramus guarauna*), also had elevated and tightly clustered $\delta^{13}C$ values (–10.1 ± 1.2 ‰), which are not commonly reported in wild animal species in the Maya region. These elevated values are likely due to the influence of the $\delta^{13}C$ values of marine-derived carbonates on the diets of the aquatic apple snails (*Pomacea* sp.) that form the bulk of limpkin diets.

Most terrestrial fauna $\delta^{15}N$ values exhibited expected trophic level effects; for example, although not a food species used by the Maya, the feline had a higher $\delta^{15}N$ value

Table 3.1: Average and standard deviation of the $\delta^{13}C$ and $\delta^{15}N$ values of freshwater, terrestrial, and marine fauna. The values of individual samples can be found in Appendix Dl.

Protein Source/Fauna	*n*	$\delta^{13}C$ (VPDB, ‰)		$\delta^{15}N$ (AIR, ‰)	
		$\bar{x}$	σ	$\bar{x}$	σ
Freshwater					
Reptile[a]	21	–21.1	4.8	+8.7	1.9
Limpkin	4	–10.1	1.2	+7.5	0.4
Terrestrial					
Dog	5	–14.4	6.5	+8.3	1.3
Turkey	13	–12.4	5.3	+7.3	1.5
Feline	1	–17.9		+8.7	
Weasel	1	–20.0		+5.7	
Nine–banded Armadillo[b]	14	–19.8	1.7	+7.3	1.3
Terrestrial Herbivore/Omnivore[c]	83	–20.6	2.7	+5.3	1.6
Marine					
Manatee	1	–4.4		+3.8	
Marine Mammal	1	–17.3		+7.5	
Sea Turtle	4	–16.8	4.4	+9.8	1.9
Snapper	1	–2.6		+8.6	

[a] Turtles were grouped with crocodiles in the freshwater reptile group, although some were not identified to species and may not be aquatic.
[b] Nine-banded armadillo are insectivorous and so were separated from terrestrial herbivores and omnivores.
[c] Terrestrial herbivores include agouti, deer, paca, and rabbit, and omnivores include opossum and peccary.

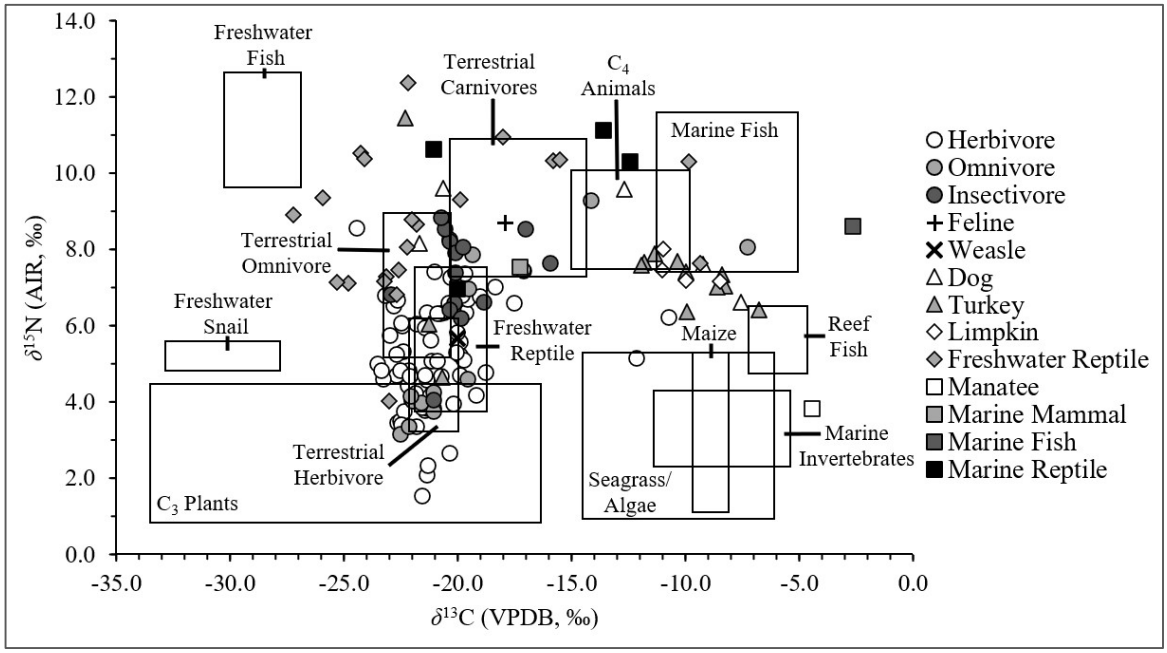

Figure 3.2: Food web reconstructed from published faunal $\delta^{13}C$ and $\delta^{15}N$ values from the Maya region (boxes) with data from this study plotted. Boxes represent average and one standard deviation of data compiled from multiple studies (Keegan and DeNiro 1988; Norr 1991; White and Schwarcz 1989; White et al. 1993; Williams et al. 2009; Wright 2006). The $\delta^{13}C$ values of modern samples were corrected for the fossil fuel (Seuss) effect by +1.5 ‰ (Marino and McElroy 1991) and more information can be found in Rand (2012). Individual species identifications, $\delta^{13}C$, and $\delta^{15}N$ values for the samples analyzed in this study can be found in Appendix D.

+8.7 ‰) than its potential prey, including terrestrial herbivores/omnivores (+5.3 ± 1.6 ‰) and the insectivorous nine-banded armadillo (+7.3 ± 1.3 ‰). However, many of the omnivorous peccaries had low δ^{15}N values that fell within the lower range for terrestrial and freshwater animals (Fig. 3.2), suggesting these peccaries derived more dietary protein from plants. In contrast, the freshwater reptiles, including various turtles and crocodiles, had the most variable δ^{13}C and δ^{15}N values (δ^{13}C = –21.1 ± 4.8 ‰, δ^{15}N = +8.7 ± 1.9 ‰; Table 3.1), reflecting their diverse dietary preferences.

The marine fauna also showed a wide range of δ^{13}C and δ^{15}N values. The sea turtles (three loggerhead sea turtles and one unidentified Cheloniidae) had δ^{13}C values lower than those previously reported for marine plants and fish (Fig. 3.2) and two had values that fell within the range of freshwater reptiles (Table 3.1). A marine mammal from Oxtankah, possibly a species of whale (Appendix D), also had a δ^{13}C value (–17.3 ‰) that plots among the terrestrial fauna (Fig. 3.2), although the δ^{15}N value (+7.5 ‰) of this specimen falls within the range of marine animals from Maya faunal assemblages (Fig. 3.2). Other marine fauna such as the Atlantic snapper (Lutianidae) and manatee (*Trichechus manatus manatus*) exhibited δ^{13}C values (–2.6 ‰ and –4.4 ‰, respectively) and δ^{15}N values (+8.6 ‰ and +3.8 ‰, respectively) consistent with their expected diets and trophic levels, as explained in the Discussion section.

3.4.2 Stable Sulfur Isotope Analysis

The δ^{34}S values of the 148 faunal samples were variable, ranging from –1.3 to +18.8 ‰ (Appendix D) and reflect dietary and locational differences. Summary statistics of the faunal δ^{34}S values reveal average values for each site and catchment type (Table 3.2,

Table 3.2: Summary statistics of the faunal $\delta^{34}S$ values from each site by source of dietary protein. All values are in units ‰ relative to VCDT excluding the number of samples, *n*. IQR = interquartile range.

Site/Protein Source	*n*	Median	IQR	Range	$\bar{x}$	1σ
Nakum						
All	16	+13.5	1.3	+5.0 to +14.6	+13.0	2.3
Terrestrial	15	+13.5	1.1	+5.0 to +14.5	+12.9	2.3
Freshwater	1	+14.6			+14.6	
Xunantunich						
Terrestrial	2	+15.8		+14.9 to +16.7	+15.8	1.3
Pacbitun						
All	19	+15.2	3.1	+6.5 to +18.8	+15.0	2.6
Terrestrial	15	+15.5	2.6	+6.5 to +18.8	+15.2	2.8
Freshwater	4	+13.6	1.3	+13.3 to +15.6	+14.1	1.1
Caye Coco						
All	26	+12.6	1.7	+8.5 to +15.9	+12.6	1.8
Terrestrial	24	+12.9	1.7	+8.5 to +15.9	+12.8	1.7
Freshwater	2	+10.4		+8.5 to +12.3	+10.4	2.7
Caye Muerto						
Terrestrial	1	+13.3			+13.3	
Chanlacan						
All	18	+13.2	1.4	+2.3 to +14.3	+11.9	3.6
Terrestrial	17	+13.2	1.2	+3.0 to +14.3	+12.5	2.8
Freshwater	1	+2.3			+2.3	
Laguna de On Island						
All	37	+13.3	3.2	+2.6 to +15.5	+11.8	3.1
Terrestrial	24	+13.5	1.5	+8.6 to +15.5	+13.1	1.5
Freshwater	12	+9.8	6.6	+2.6 to +13.6	+9.0	3.8
Marine	1	+14.2			+14.2	
Laguna de On Shore						
Terrestrial	1	+15.8			+15.8	
Ichpaatun						
Terrestrial	1	+16.5			+16.5	
Oxtankah						
All	7	+16.0	0.8	+14.8 to +18.0	+16.2	1.0
Terrestrial	6	+16.0	0.8	+14.8 to +18.0	+16.2	1.0
Marine	1	+16.1			+16.1	
Vista Alegre						
All	17	+14.2	2.5	–1.3 to +16.5	+12.8	4.7
Terrestrial	8	+15.0	1.7	+12.6 to +16.5	+14.7	1.3
Freshwater	5	+14.2	2.5	+3.4 to +16.0	+12.6	5.3
Marine	4	+12.3	8.6	–1.3 to +13.6	+9.2	7.1
San Miguelito						
Terrestrial	2	+13.0		+12.3 to +13.7	+13.0	1.0
Moho Cay						
Marine	1	+2.4			+2.4	

Fig. 3.3). Sixteen outlier values are present at seven of the sites (Fig. 3.3); however, when the fauna from each site were categorized by source of their dietary protein (i.e., terrestrial, freshwater, or marine), only nine δ^{34}S values are statistical outliers (Fig. 3.4). Eight terrestrial animals with outlying δ^{34}S values may represent nonlocal individuals from isotopically distinct regions and one freshwater animal with an outlying value at Vista Alegre likely reflects species differences in sources of dietary protein.

The δ^{34}S values of freshwater fauna were generally lower than those of terrestrial taxa from the same site, although the sample size of marine animals from most sites was too small for comparison (Table 3.2). When the statistically outlying values were removed, this difference was statistically significant at Laguna de On Island ($t = -3.898$, $df = 12.036$,

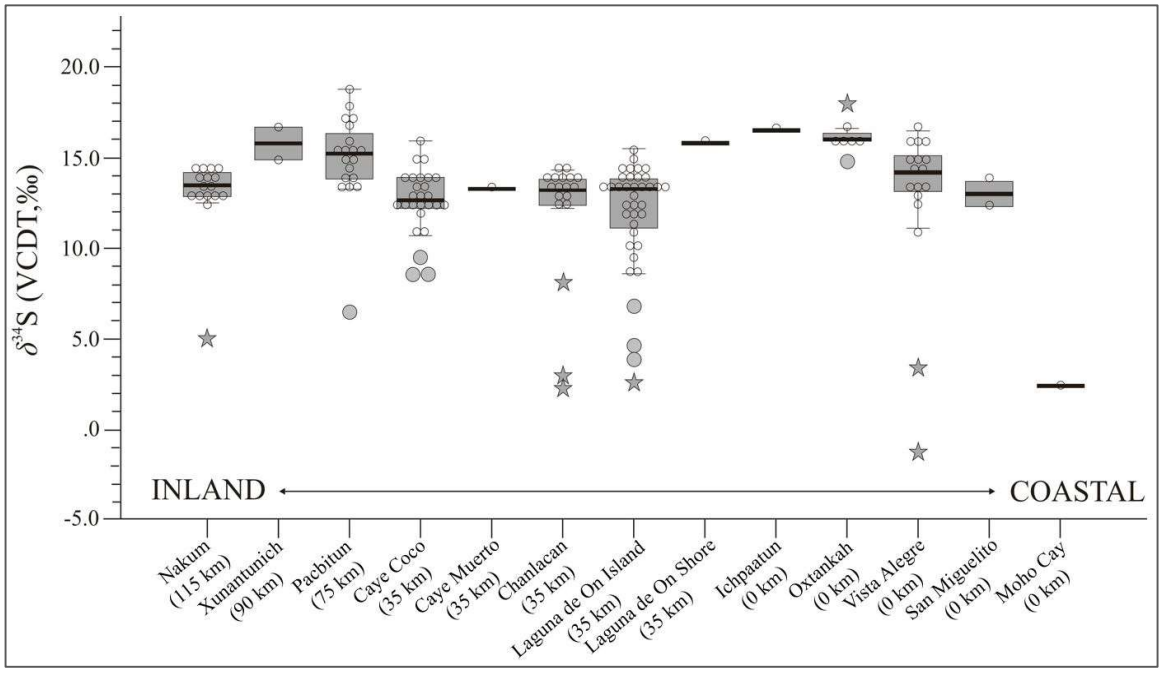

Figure 3.3: Boxplots of the faunal δ^{34}S values from the sites listed in Table 3.2 arranged by distance from the coast in km beneath site name. Individual data points (circles) have been superimposed over the boxplots, outliers are identified as larger filled circles that fall beyond the whiskers, and extreme outliers are identified as filled stars (see Appendix A for how outliers were identified using the IQR method).

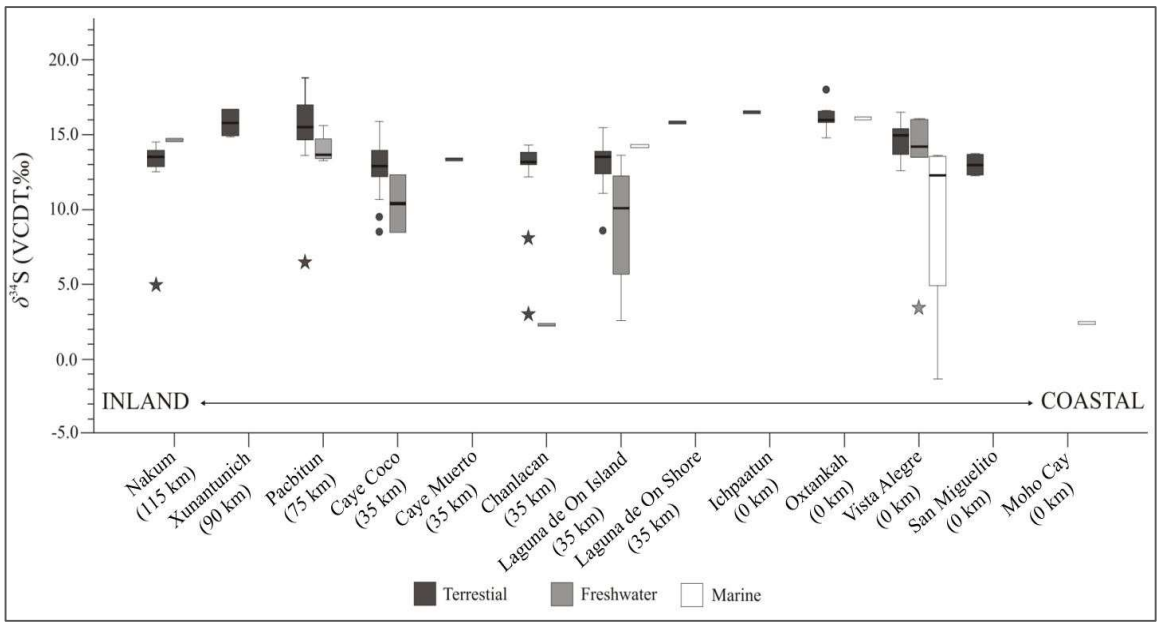

Figure 3.4: Boxplots of the faunal δ^{34}S values from each site arranged by distance from the coast in kilometers (km) beneath the site name and grouped by source of dietary protein (terrestrial, freshwater, or marine) based on taxa identification. Circles indicate outliers whereas stars represent extreme outliers (see Appendix A for details). See Table 3.2 for the number of samples in each category for each site.

p = 0.002) and Pacbitun (U = 46.5000, p = 0.046), but not at Caye Coco (U = 38.50, p = 0.087), and the differences in the δ^{34}S values among freshwater, marine, and terrestrial taxa from Vista Alegre also were not statistically significant (W = 3.424, df = 2, p = 0.180). This demonstrates that lumping the δ^{34}S values of fauna from different ecosystems together may overestimate the number of nonlocal individuals at a site, and it is therefore necessary to statistically evaluate the δ^{34}S values of marine, freshwater, and terrestrial animals separately when identifying statistical outliers and developing local baseline ranges.

The δ^{34}S values of the seven marine fauna samples ranged from –1.3 ‰ to +16.1 ‰ and include three sea turtles from Vista Alegre (+12.7 ± 1.4 ‰) and one from Laguna de On Island (+14.2 ‰), a Caribbean manatee from Moho Cay (+2.4 ‰), an Atlantic snapper (–1.3 ‰) from Vista Alegre, and a marine mammal from Oxtankah (+16.1 ‰)

(Fig. 3.5; Appendix D). Outlying values were not identified among the small sample of marine taxa at each site.

The δ^{34}S values of freshwater taxa (n=25) were also variable, ranging from +2.3 to +16.0 ‰ and reflect multiple trophic levels and species- and individual-specific dietary behaviour (Fig. 3.6; Appendix D). However, trends in the δ^{34}S values were apparent in the average faunal values at these sites. For example, the Mesoamerican sliders and other

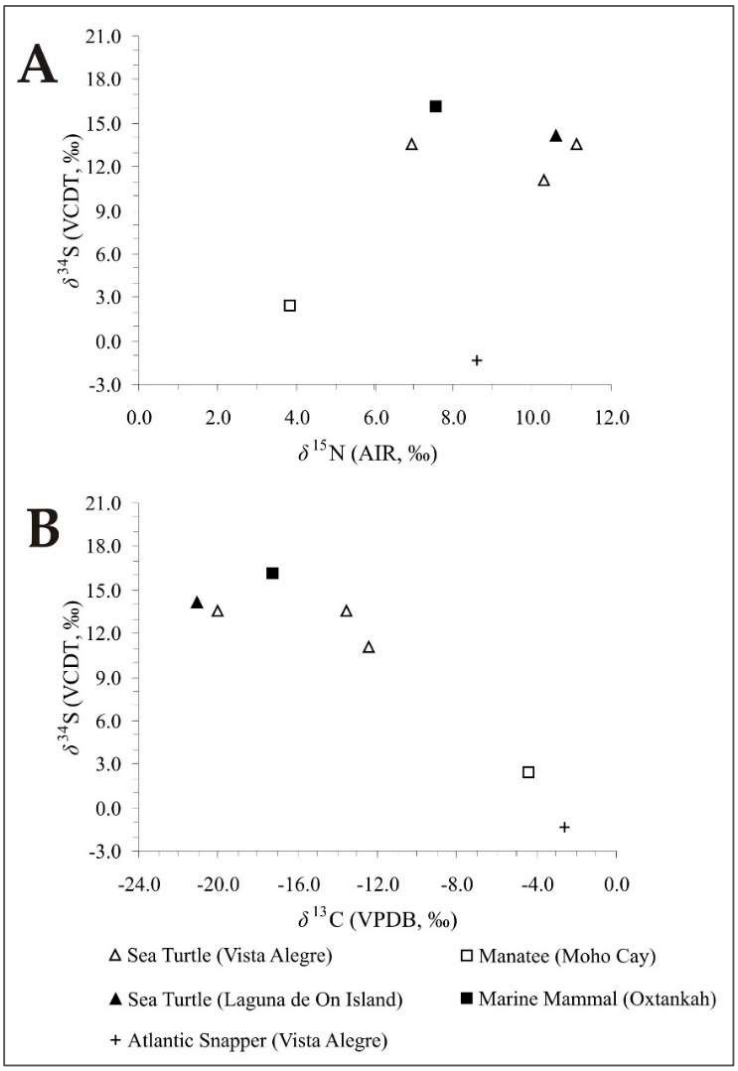

Figure 3.5: The δ^{34}S values from fauna reliant on marine protein by site and taxa plotted against (A) δ^{15}N and (B) δ^{13}C values from the same samples.

turtles (+9.3 ± 4.0 ‰) and crocodiles (+8.3 ± 3.7 ‰) from Laguna de On Island had similar average δ^{34}S values that were slightly lower than those of the Mesoamerican sliders from Caye Coco (+10.4 ± 2.6 ‰), but much lower than the Mesoamerican slider from Nakum (+14.6 ‰) and turtles from Pacbitun (+14.0 ± 1.1 ‰) (Fig. 3.6). Several specimens had much lower δ^{34}S values than other freshwater animals, including a crocodile (+4.6 ‰),

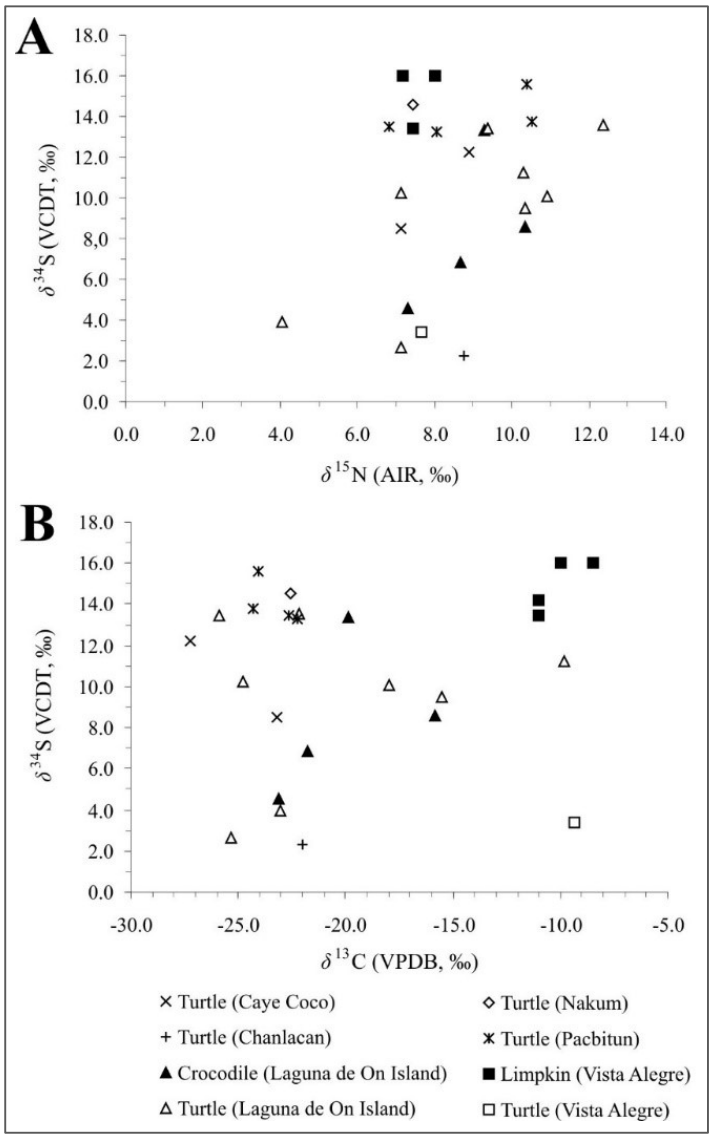

Figure 3.6: The δ^{34}S values from fauna reliant on freshwater protein by site and taxa plotted against (A) δ^{15}N and (B) δ^{13}C values from the same samples.

Mesoamerican slider (+2.6 ‰), and another turtle (+3.9 ‰) from Laguna de On Island, a pond turtle from Chanlacan (+2.3 ‰), and a Mesoamerican slider from Vista Alegre (+3.4 ‰). Finally, the average δ^{34}S value of the four Vista Alegre limpkins (+14.9 ± 1.3 ‰) was elevated compared to that of the turtle (+3.4 ‰; Fig. 3.4), reflecting differing sources of dietary protein for these freshwater species.

The δ^{34}S values of the terrestrial fauna (n = 116) ranged from +3.3 to +18.8 ‰ (Appendix D) and were significantly different (H = 37.712, df = 3, $p < 0.001$) among sites depending on the age of the underlying geology and distance from the coast (Table 3.3, Fig. 3.7). The limestone bedrock beneath the sites included in this study dates to three different periods, which from oldest to youngest are Mesozoic (Pacbitun and Xunantunich), Paleogene/Neogene (Caye Coco, Caye Muerto, Chanlacan, Laguna de On Island and Shore, Nakum, Oxtankah, and Ichpaatun), and Quaternary (Vista Alegre and San Miguelito). Vista Alegre, San Miguelito, Oxtankah, and Ichpaatun are considered coastal while the remaining sites are classified as inland (i.e., ≥ 20 km from the coast; Richards et al. 2001). Terrestrial fauna from most coastal sites exhibited δ^{34}S values influenced by sea spray sulfate that were significantly higher ($p < 0.001$) than values of terrestrial fauna from inland sites located on Paleogene/Neogene limestones (Table 3.3, Fig. 3.7). Faunal δ^{34}S values from sites located on Quaternary limestones did not significantly differ from those on Paleogene/Neogene limestones in coastal (p = 0.323) or inland (p = 0.216) locations. The faunal δ^{34}S values from inland sites on Mesozoic limestone were statistically similar to those from coastal sites on Quaternary (p = 0.792) or Paleogene/Neogene (p = 1.000) limestone and were significantly higher than those from inland sites on younger Paleogene/Neogene limestones ($p < 0.001$; Fig. 3.7).

Table 3.3: Average and standard deviation of the $\delta^{34}S$ values of terrestrial, freshwater, and marine fauna by age of underlying geology and distance of each site from the coast.

Geography/Site	Distance to Coast (km)	Terrestrial $\delta^{34}S$ (VCDT, ‰)			Freshwater $\delta^{34}S$ (VCDT, ‰)			Marine $\delta^{34}S$ (VCDT, ‰)		
		n	$\bar{x}$	**1σ**	***n***	$\bar{x}$	**1σ**	***n***	$\bar{x}$	**1σ**
Inland Mesozoic										
Xunantunich	90	2	+15.8	1.2	0	–	–	0	–	–
Pacbitun	75	14	+15.8	1.5	4	+14.0	1.1	0	–	–
All		16	+15.8	1.5	4	+14.0	1.1	0	–	–
Inland Paleogene/Neogene										
Nakum	115	14	+13.5	0.7	1	+14.6	–	0	–	–
Caye Coco	35	22	+13.1	1.2	2	+10.4	2.6	0	–	–
Caye Muerto	35	1	+13.3	–	0	–	–	0	–	–
Chanlacan	35	15	+13.4	0.6	1	+2.3	–	0	–	–
Laguna de On Island	35	23	+13.3	1.1	12	+9.0	3.8	1	+14.2	
Laguna de On Shore	35	1	+15.8	–	0	–	–	0	–	–
All		76	+13.3	1.0	16	+9.1	4.0	1	+14.2	
Coastal Mesozoic										
San Miguelito	0	2	+13.0	1.0	0	–	–	0	–	–
Vista Alegre	0	8	+14.7	1.3	4[a]	+14.9	1.3	3[b]	+12.7	1.4
Moho Cay	0	0	–	–	0	–	–	1	+2.4	–
All		10	+14.3	1.4	4	+14.9	1.3	4[b]	+7.9	6.9
Coastal Paleogene/Neogene										
Oxtankah	0	5	+15.8	0.6	0	–	–	1	+16.1	–
Ichpaatun	0	1	+16.5	–	0	–	–	0	–	–
All		6	+16.0	0.6	0	–	–	1	+16.1	–

[a] Freshwater turtle (ID 4523) was removed from the Vista Alegre freshwater data set because it had an outlying $\delta^{34}S$ value compared to the limpkins due to differing sources of dietary protein.
[b] Snapper (ID 4522) was removed from Vista Alegre marine data set because although it was not a statistical outlier, its $\delta^{34}S$ value was much lower than those of the sea turtles from Vista Alegre, reflecting differing sources of dietary sulfur between species.
Note: Eight terrestrial faunal (IDs 3445, 4161, 4261, 4267, 4293, 4305, 4325, and 4540) samples were excluded from the calculation of the regional average values and standard deviations because their $\delta^{34}S$ values were statistical outliers and they were therefore interpreted as nonlocal individuals.

Nine faunal $\delta^{34}S$ values from seven sites were identified as statistical outliers for each source of protein by site using the IQR method (Fig. 3.4), one of which was the Mesoamerican slider from Vista Alegre mentioned above. The eight remaining outlying $\delta^{34}S$ values were from terrestrial specimens from six sites (Fig. 3.7) but were identified as

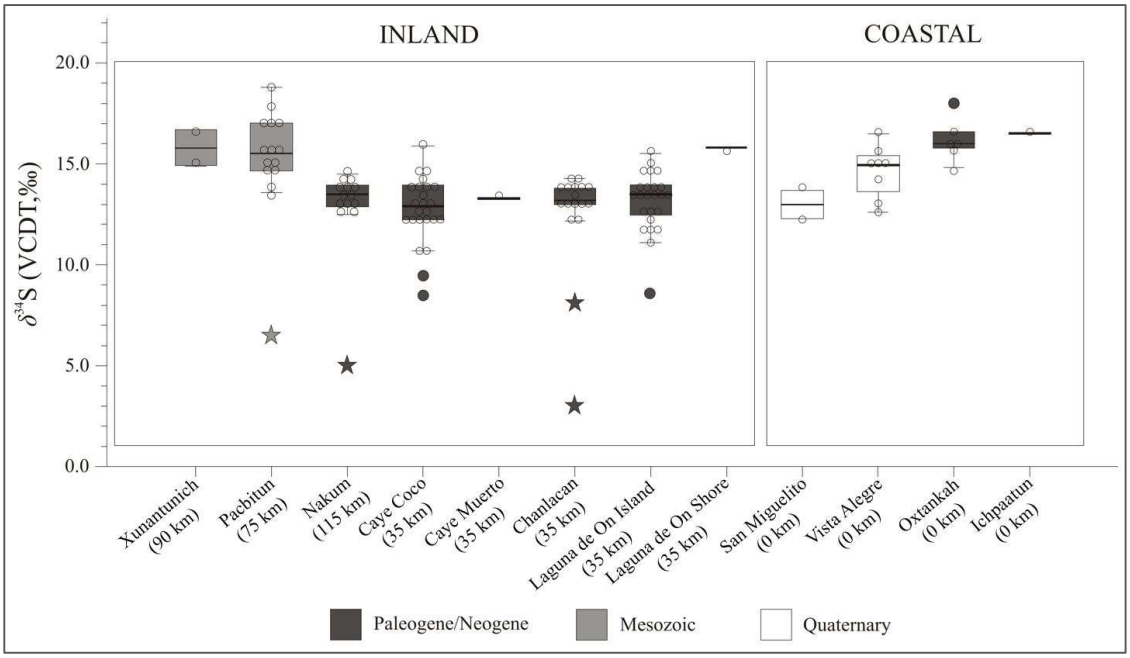

Figure 3.7: Boxplots of the $\delta^{34}S$ values from fauna that consumed terrestrial protein by site. Sites have been grouped based on their inland or coastal locations (with distance from the coast indicated in kilometers (km) beneath the site name) and the age of the underlying limestone of each site is distinguished by colour. Datapoints have been individually plotted (circles), filled circles beyond the whiskers represent outliers, and filled stars represent extreme outliers (see Appendix A for details).

nonlocal animals from isotopically distinct regions. Most nonlocal fauna identified to date in the Maya region consist of large or medium taxa such as deer, peccary, or dog (e.g., Sharpe et al. 2016; Thornton 2011; Yaeger and Freiwald 2009); however, the $\delta^{34}S$ values presented in this study show that smaller game animals were also acquired nonlocally. One agouti from Oxtankah (1/6 = 16.7%) had a high outlying value (+18.0 ‰); all other outliers had lower $\delta^{34}S$ values than the remaining terrestrial animals from the same site. These samples included a dog and armadillo from Caye Coco (2/24 = 8.3%), a dog and peccary from Chanlacan (2/17 = 11.8%), one white-tailed deer each from Laguna de On Island (1/24 = 4.2%) and Pacbitun (1/15 = 6.7%), and a probable white-tailed deer from Nakum (1/15 = 6.7%). No outliers were identified among the eight terrestrial samples from Vista

Alegre, and it was not possible to identify outliers from Xunantunich, Caye Muerto, Laguna de On Shore, Ichpaatun, or San Miguelito due to small sample sizes.

3.5 Discussion

3.5.1 Variation of Faunal δ^{34}S Values in the Maya Region

The faunal δ^{34}S values from Maya sites are variable but show patterns among the marine, freshwater, and terrestrial species. Specifically, marine animals in this study exhibited lower δ^{34}S values than hypothesized, those of freshwater species varied by location and the dietary preferences of specific species, and after removing nonlocal values, the local terrestrial fauna δ^{34}S values differed based on the distance from the coast and the age of the underlying limestone.

Archaeological marine fish and mammals from the open ocean typically exhibit δ^{34}S values between +14 to +19 ‰ (Nehlich and Richards 2009; see also Fornander et al. 2008); however, only the values of the marine mammal from Oxtankah (+16.1 ‰) and the sea turtle from Laguna de On Island (+14.2 ‰) fell within this range. Instead, most marine taxa from Maya sites had δ^{34}S values less than +14 ‰, likely reflecting the influence of DSR or freshwater discharge on the δ^{34}S values of plants at the base of some marine food chains, as has been found in modern saltmarsh and estuarian ecosystems (Kanaya et al. 2008; Mizota et al. 1999; Peterson et al. 1986; Yamanaka et al. 2000). For example, manatee are herbivorous generalized mixed feeders that consume seagrass and other submerged aquatic vegetation, including macroalgae and mangroves (MacFadden et al. 2004; McKillop 1985), all of which exhibit low modern δ^{34}S values due to DSR (Canfield 2001; Fry et al. 1982, 1988; Raven and Scrimgeour 1997). Manatee, which are rare in Maya faunal assemblages,

also frequent estuarine areas (McKillop 1985) that are likely to have lower bioavailable δ^{34}S values resulting from freshwater discharge, as has been found in other archaeological studies (Craig et al. 2006; Fornander et al. 2008; Linderholm et al. 2008b). The Atlantic snapper had the lowest δ^{34}S value in this study (–1.3 ‰), although its elevated δ^{13}C and δ^{15}N values are consistent with those of other archaeological carnivorous reef fish (Williams et al. 2009). Snappers frequent reefs, but also mud-bottom habitats (Gallaway et al. 2009; Szedlmayer and Lee 2004) with anaerobic substrates that facilitate DSR (Kanaya et al. 2008; Yamanaka et al. 2000), which would explain the low δ^{34}S value of this specimen. Finally, the more variable δ^{34}S values among the loggerhead sea turtles reflect their diets as generalist carnivores that feed on seasonally diverse foods (Hatase et al. 2002; Plotkin et al. 1993; Tucker et al. 2014; Vander Zanden et al. 2010). As with the marine animals from Maya sites, an archaeological marine turtle had a lower δ^{34}S value (+8.8 ‰) relative to that of a dolphin in Trinidad (+17.0 ‰; Sparks and Crowley 2018:973), further indicating that dietary differences among marine species consumed by archaeological humans must be considered when interpreting stable sulfur isotope values.

Although the δ^{34}S values of freshwater taxa were variable depending on site location and the diets of individual specimens, they were generally lower than those of both terrestrial and marine animals from the same site (Table 3.2). Other studies have found the δ^{34}S values of archaeological freshwater fauna vary depending on the geology underlying the freshwater ecosystem. For example, freshwater fish from the sulfur-poor clays near Oxfordshire, UK during the Roman period had δ^{34}S values as low as –20.9 to –17.3 ‰ (Nehlich et al. 2011), whereas those from freshwater lakes and rivers throughout the Quaternary sediments near Late Bronze Age Chicha in Siberia were higher, ranging from

+14.8 to +21.8 ‰ (Privat et al. 2007). While the underlying limestone geology has also influenced the δ^{34}S values of the freshwater taxa included in this study, the variability among individuals reflects individual dietary preferences as well as the numerous sulfate inputs in freshwater ecosystems. The turtles from Pacbitun had the highest and least variable δ^{34}S of the freshwater reptiles, likely because they were acquired from nearby well-oxygenated springs, creeks, and streams (Emery and Healy 2014). The more varied reptile values from Caye Coco, Chanlacan, and Laguna de On Island, which included some of the lowest reported in this study, show that the diets of some freshwater animals were influenced by DSR in the sediments of nearby lagoons (Masson 2004), while others with comparatively elevated values were not. This is also evident at Vista Alegre, where the δ^{34}S value of the Mesoamerican slider (+3.4 ‰) was considerably lower than those of the limpkins (+14.7 ± 1.3‰). The environment of this coastal port site is characterized by a flooded mangrove forest as well as wetlands (Beddows et al. 2016), and it appears that the dietary sulfur of the turtle was derived from a wetland or mangrove ecosystem influenced by DSR, whereas the diets of the freshwater apple snails consumed by the limpkins may have been influenced by the elevated δ^{34}S values of marine sulfate.

Before the terrestrial fauna δ^{34}S values can be used to evaluate the hypothesized variation in δ^{34}S values in the Northern and Eastern Lowlands, it is necessary to identify nonlocal animals so their values can be removed prior to calculating the local range for each site. The presence of nonlocal taxa at a site identified zooarchaeologically, such as the presence of a sea turtle at the inland Laguna de On Island site or a brocket and white-tailed deer at the island site of San Miguelito off the coast of Cancun, is clear evidence for the exchange of animal resources from different environments. Stable sulfur isotope analysis

offers an additional means of identifying nonlocal animals from isotopically distinct regions that may otherwise be considered locally acquired.

Nonlocal terrestrial animals were distinguished by their outlying $\delta^{34}S$ values at 6 of the 13 sites included in this study, comprising between 4.2 % and 16.7 % of the sampled faunal assemblages. The extremely high $\delta^{34}S$ value of the agouti from Oxtankah (+18.0 ‰) was notable, given that the diets of the local animals were already substantially elevated at this coastal site due to sea spray (+15.8 ± 0.6 ‰). Due to the considerable overlap of the $\delta^{34}S$ values (i.e., equifinality) between coastal fauna and those located on sites underlain by limestone, it is difficult to propose a probable place of origin for this specimen as this time. However, the extremely low $\delta^{34}S$ values of the deer, peccary, and armadillo from the remaining sites are unlikely to have been derived from an area underlain by limestone, and instead reflect the origin of these animals from an area where the geology is hypothesized to exhibit lower $\delta^{34}S$ values, such as the Maya Mountains or Highlands (Fig. 3.1). Based on proximity, Rand et al. (2020a) proposed that the probable white-tailed deer from Nakum may have been imported from the Maya Mountains. These data support a previous hypothesis that specialized hunting of wild terrestrial game may have been practiced in less populated areas, including the Maya Mountains (McAnany 1989; Yaeger and Freiwald 2009), and the procured animals may have been exchanged as food, tribute, or ritual items (Thornton 2011).

Most of the nonlocal animals identified in this study belong to species (i.e., deer, dog, and peccary) that strontium and oxygen isotope data show were acquired nonlocally by the Maya (Sharpe et al. 2018; Sugiyama et al. 2018; Thornton 2011; Thornton et al. 2016; Yaeger and Freiwald 2009). This is the first study to isotopically identify a nonlocal

agouti and armadillo, which was surprising given the assumption that the Maya obtained small animals locally. It is unlikely that the nonlocal $\delta^{34}S$ values of these specimens reflect differential dietary preferences among terrestrial species, as both have values that differ from others of their species from the same site. This demonstrates that caution is necessary when assuming that small mammals with narrow home ranges will represent local isotopic baselines, especially when small sample sizes are considered.

When the eight nonlocal values are removed from the data set, the patterns in the $\delta^{34}S$ values of the local terrestrial fauna from coastal sites analyzed in this study are consistent with the hypothesized elevated values in coastal areas (Fig. 3.1). The average $\delta^{34}S$ values of terrestrial fauna from Vista Alegre, Oxtankah, and Ichpaatun exceed +14 ‰ (Table 3.3), evidencing the influence of sea spray on dietary sulfur at these coastal sites, as has been found at other coastal archaeological contexts (Fornander et al. 2008; Kinaston et al. 2014; Richards et al. 2001; Stantis et al. 2015). The slightly lower $\delta^{34}S$ values from the brocket deer (+13.7 ‰) and white-tailed deer (+12.3 ‰) from San Miguelito (see Fig. 3.7) suggest these animals may have been hunted in an inland area less influenced by sea spray sulfate and were subsequently transported to this island site.

The local $\delta^{34}S$ values of terrestrial fauna from inland Maya sites also varied depending on the age of the underlying geology, although not as expected. Rather than having lower $\delta^{34}S$ values as hypothesized in Section 3 and Figure 3.1, sites located on Mesozoic limestone (Xunantunich and Pacbitun) had the highest average terrestrial fauna $\delta^{34}S$ values, which were indistinguishable from those at coastal sites. The Xunantunich specimens were analyzed at a different laboratory, which may introduce some variation; however, the values from Pacbitun remain significantly elevated ($H(3) = 37.862$, $p <$

0.001), specifically relative to Inland Paleogene/Neogene ($p < 0.001$) and Coastal Quaternary ($p < 0.001$) sites and are indistinguishable from Coastal Paleogene/Neogene sites ($p = 1.000$). The elevated $\delta^{34}S$ values of animals from sites underlain by Mesozoic limestone were unexpected, given that older limestones typically exhibit slightly lower but overlapping values with Paleogene/Neogene and Quaternary evaporites (Bottrell and Newton 2006; Claypool et al. 1980; Fig. 3.1). Sea spray is an unlikely explanation for these elevated values, given that the sampled sites were located a considerable distance from any coast. It is also unlikely that all of these animals were imported from coastal areas, as the Maya typically utilized local faunal resources (Götz 2008; Jiménez Cano and Sierra Sosa 2015; but see Thornton 2011; Yaeger and Freiwald 2009). Rather, it is possible that these elevated $\delta^{34}S$ values were derived from plants that assimilated sulfur from gypsum deposits that are commonly found throughout the Mesozoic soils of the Yucatan (Perry et al. 2009).

The elevated terrestrial faunal $\delta^{34}S$ values from inland Maya sites also demonstrate why it is necessary to establish local baselines for specific regions. For example, the local terrestrial faunal $\delta^{34}S$ values from inland Maya sites (+10.7 to +18.8 ‰) were elevated compared those reported from inland archaeological contexts from Europe (-13.5 to +13.7 ‰; Fornander et al. 2008; Linderholm et al. 2008b; Nehlich et al. 2010, 2011; Richards et al. 2001), Asia (+3.0 to +10.6 ‰; Guo et al. 2018; Irvine and Erdal 2020; Privat et al. 2007) and the Caribbean (+2.4 to +9.2 ‰; Sparks and Crowley 2018). It has been previously proposed that human or animal bone collagen from inland sites with $\delta^{34}S$ values that exceed +14 ‰ represent nonlocal individuals from coastal areas whose diets were influenced by sea spray (Madgwick et al. 2019a; Richards et al. 2001). While this certainly holds true for inland sites located on lithologies with lower $\delta^{34}S$ values, the results of this study

demonstrate this is not applicable in regions underlain by marine evaporites such as limestone that exhibit elevated values, as has been observed elsewhere (Curto et al. 2019; Privat et al. 2007). This emphasizes the necessity of establishing local baseline δ^{34}S values for the interpretation of subsistence, migration, and animal exchange in the past.

3.5.2 Implications for Studies of Maya Diet, Animal Exchange, and Migration

Archaeological studies elsewhere in the world have investigated the use of sulfur isotope analysis for distinguishing between terrestrial, freshwater, and marine protein in human diets (Craig et al. 2006; Curto et al. 2019; Leach et al. 1996; Nehlich et al. 2010, 2011, 2012; Privat et al. 2007; Richards et al. 2001; Sayle et al. 2013). At Maya sites in the Eastern and Northern Lowlands, sulfur isotope analysis appears useful for identifying the consumption of freshwater protein but may be inappropriate for differentiating terrestrial and marine diets. This is because the elevated δ^{34}S values from terrestrial animals derived from the underlying limestone geology overlapped with the values of marine fauna, many of which had lower δ^{34}S values than expected for archaeological marine taxa (+14 to +19 ‰; Nehlich and Richards 2009; Fornander et al. 2008) likely due to the influence of DSR. This suggests that it will be difficult to differentiate between marine- and terrestrial-based diets among the Maya. However, future studies should consider that the δ^{34}S values of methionine from lime-processed maize may overwhelm those derived from animal protein in Maya bone collagen.

In contrast, freshwater fauna generally had lower δ^{34}S values than terrestrial and marine animals, indicating sulfur isotope analysis may be useful for distinguishing Maya freshwater protein consumption, as has been observed in other archaeological contexts

(Nehlich et al. 2010; Privat et al. 2007). This is an important area for future research, as Maya reliance on freshwater resources has been relatively understudied. For example, turtles are recognized food taxa, as is the freshwater *jute* snail (*Pachychilus* ssp.) but both are interpreted as supplemental rather than as primary sources of dietary protein (Boileau and Stanchly 2020; Healy et al. 1990; Masson 2004). Fish remains are found at sites adjacent to lakes, estuaries, or the sea (e.g., Götz 2008; Jiménez Cano and Sierra Sosa 2015; Masson 2004; Thornton 2011) but are notably absent from sites located near rivers (Freiwald 2010). This cannot be fully explained by recovery methods (see Emery 2004b; Masson 2004) and may reflect the poor preservation of archaeological fish bone (Szpak 2011), cultural practices such as filleting or salting fish where consumption and preparation locations differed (Pohl 1983; but see McKillop and Aoyama 2018), or even a real cultural aversion to fish as a food source (Pohl 1983). The application of stable sulfur isotope analysis as well as compound-specific isotopic analysis of individual amino acids (Webb et al. 2015) may address some of these questions, providing additional insights into Maya freshwater protein consumption.

Stable sulfur isotope analysis has successfully identified nonlocal individuals as those with statistically distinct $\delta^{34}S$ values in other archaeological contexts (Nehlich et al. 2012; Vika 2009). Based on the identification of nonlocal faunal specimens in this study (see also Rand et al. 2020a), it is also reasonable to propose that nonlocal Maya individuals may be similarly identified. Importantly, sulfur isotope analysis tracks migration near the end of life because bone collagen $\delta^{34}S$ values represent an average derived from dietary protein consumed from adolescence to the end of life, depending on which bone is sampled and individual physiology in bone turnover rates (Hedges et al. 2007; Matsubayashi and

Tayasu 2019; Parfitt 2001; Richards et al. 2003; Webb et al. 2017). In contrast, strontium and stable oxygen isotope analysis are typically conducted on tooth enamel due to issues of diagenesis (Budd et al. 2000; Hoppe et al. 2003), and thus identify nonlocal individuals who consumed isotopically distinct food and water during the period in childhood when their teeth formed (Moradian-Oldak 2009). Thus, a multi-isotopic approach that incorporates data from tissues that form at different periods can contribute to a more detailed understanding of migration over the life course of an individual. Using multiple isotopic analyses can also circumvent the limitations associated with the equifinality of $\delta^{34}S$ values (as well as strontium and oxygen isotope values; see Price et al. 2010) over large regions of the Northern and Southern Lowlands to provide additional means for identifying nonlocal individuals whose $\delta^{34}S$ values may fall within the local range.

3.6 Chapter 3 Summary and Conclusions

The $\delta^{13}C$ and $\delta^{15}N$ results from the faunal samples analyzed here are consistent with those reported in previous studies, and the faunal $\delta^{34}S$ values provide important insights into the variation of environmental $\delta^{34}S$ values throughout the Maya region. The $\delta^{34}S$ values of marine animals were lower than expected and were likely influenced by DSR and freshwater discharge into coastal ecosystems. The low yet variable $\delta^{34}S$ values of freshwater taxa are likely derived from DSR, the catchments and sulfur sources of freshwater systems, and the individual dietary preferences of the sampled animals. As observed in other contexts, sea spray elevated the $\delta^{34}S$ values of coastal terrestrial animals; however, inland terrestrial fauna from sites on Mesozoic limestone also had elevated values rendering them indistinguishable from values at coastal sites. Importantly, these results

demonstrate the necessity of establishing separate ranges of local $\delta^{34}S$ values for terrestrial, freshwater, and marine protein sources at any given site.

The faunal results indicate that stable sulfur isotope analysis offers a potential tool for differentiating terrestrial and freshwater diets at inland sites, although this is complicated by factors that influence faunal $\delta^{34}S$ values, including the type and age of the underlying geology, distance from the coast and sea spray, DSR in aquatic environments, riverine sulfate from multiple sources, and the diets of individual organisms. However, the identification of nonlocal animals at six of the thirteen sites in this study also demonstrates the potential of this technique not only for studies of animal exchanged for both subsistence but also as organic artifacts but also migration among the Maya. The nonlocal $\delta^{34}S$ values of small mammals show that the Maya acquired fauna from diverse catchments and that animal exchange extended to more species than previously known. The identification of nonlocal faunal indicates this technique will be similarly useful for identifying nonlocal Maya individuals. The analysis of stable sulfur isotopes from human bone collagen in conjunction with strontium and stable oxygen isotope analysis of tooth enamel from the same individual may also provide insight into movement at the end of life, or even if an individual moved multiple times, and can help circumvent equifinality associated with any one isotope system.

Stable sulfur isotope analysis is a relatively new method in archaeological studies compared to more established techniques such as strontium and stable carbon, nitrogen, and oxygen isotope analysis. As such, more research is needed to understand the influence of preparation techniques and interlaboratory analyses on archaeological bone collagen $\delta^{34}S$ values. Additional research is also necessary to better characterize the $\delta^{34}S$ values of

marine, freshwater, and terrestrial resources in the Maya region to improve understandings of the food webs at each site and provide baseline isotopic data for studies of human diet and movement. Expanding this research into the Highlands, Pacific Coast, Motagua Valley, and the Maya Mountains will also reveal how much variation in $\delta^{34}S$ values exists in the Maya region, and more broadly across Mesoamerica. This study represents the first step in a region-wide analysis of the utility of stable sulfur isotope analysis in Maya archaeology and the application of this technique in a tropical continental archaeological context more generally. Future multi-isotopic studies that include stable sulfur isotope analysis will undoubtedly contribute to archaeological interpretations of Maya subsistence practices and migration.

CHAPTER 4

STABLE SULFUR ISOTOPE EVIDENCE OF SUBSISTENCE PRACTICES AND MIGRATION AMONG THE MAYA[8]

Isotopic techniques offer an important tool for the study of subsistence strategies and migration in archaeological contexts and therefore contribute to broader interpretations of sociocultural processes in past societies (Anthony 1990; Cabana and Clark 2011a; Gumerman 1997; Hastorf 2017; van der Veen 2003). In the Maya region, stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope analyses have been extensively used to investigate Maya consumption of maize and animal protein (Somerville et al. 2013; Tykot 2002), and stable oxygen ($\delta^{18}O$) and radiogenic strontium ($^{87}Sr/^{86}Sr$) isotope analyses have contributed to

[8] This chapter was written solely by the author, although the results will be published in several venues. The data from Xunantunich, San Lorenzo, Caledonia, and Pacbitun is included in an article currently under review by *PLoS ONE* coauthored with principal author Dr. Claire Ebert, and coauthors Dr. Kirsten Green-Mink, Dr. Julie Hoggarth, Dr. Carolyn Freiwald, Dr. Jaime Awe, Dr. Willa Trask, Dr. Jason Yaeger, Dr. M. Kathryn Brown, Dr. Christophe Helmke, Rafael Guerra, Dr. Marie Danforth, and Dr. Douglas Kennett as part of a broader study of stable sulfur isotope analysis of human remains from Maya sites located in the Belize Valley and surrounding area (Ebert et al. in review). The Caledonia data was presented as a paper at the 48th Annual Meeting of the Canadian Association for Physical Anthropology in November 2020 coauthored by Dr. Freiwald and Dr. Vaughan Grimes (Rand et al. 2020b), and the Xunantunich and San Lorenzo data was also presented at the Bioarchaeology Early Career Conference (BECC) 2021 and coauthored with Dr. Freiwald, Dr. Jason Yaeger, Dr. M. Kathryn Brown, and Dr. Grimes (Rand et al. 2021b). The human isotopic data from Chac and Calakmul are detailed in a report submitted to Mexico's Instituto Nacional de Antropología e Historia (INAH). The author also intends to publish the data from Mission San Bernabé in collaboration with Dr. Freiwald, Dr. Kathrine Miller Wolf, and Dr. Timothy Pugh as part of a multidisciplinary study of diet and health during the Colonial period. Finally, the Nakum data has been incorporated into a multi-isotopic case study of subsistence and migration at the site presented in Chapter 5 and published in the *Journal of Archaeological Science: Reports* (Rand et al. 2020a) in collaboration with Varinia Matute, Dr. Grimes, Dr. Freiwald, Dr. Jarosław Źrałka, and Dr. Wiesław Koszkul.

reconstructing migration to Maya sites (Price et al. 2008; Scherer et al. 2015; Wright 2012; see Chapter 2).

Stable sulfur isotope ($\delta^{34}S$) analysis is a relatively new technique that has been increasingly applied to the study of subsistence and migration in archaeological societies (Nehlich 2015; see also Chapter 1). The considerable archaeological and isotopic databases available in the Maya region provide an excellent framework in which to test the utility of stable sulfur isotope analysis for identifying Maya diet and migration. Indeed, recent sulfur isotope analysis of human bone collagen from Cahal Pech and Caledonia have demonstrated the potential of this technique in Maya archaeology (Awe et al. 2017; Green 2016; Rand and Grimes 2017). Drawing on previously published isotopic and archaeological evidence, as well as the faunal isotopic baseline data from Chapter 3 (Rand et al. 2021a), this chapter interprets new $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values from 49 Maya individuals from seven Maya sites ranging from the Preclassic to Colonial periods. The results demonstrate how the integration of sulfur isotope analyses into a multi-isotopic approach provides new insights into Maya subsistence strategies and migration.

4.1 Principles of Stable Isotope Analysis

Because the isotopic values of consumer tissues reflect those of protein in their diets (Ambrose and Norr 1993; Richards et al. 2003; Webb et al. 2017), these techniques are useful for reconstructing past subsistence practices as well as the source of dietary protein. The systematics of stable sulfur, carbon, and nitrogen isotope analyses and how they vary in the Maya region are briefly reviewed here and are discussed in detail in Chapter 3.

Stable carbon isotope ($\delta^{13}C$) analysis is used to differentiate between sources of

dietary protein derived from plants at the base of the food chain that use the C_3 (Calvin-Benson) and C_4 (Hatch-Slack) photosynthetic pathways (Smith and Epstein 1971; van der Merwe 1982). The $\delta^{13}C$ values of plants are passed on to their consumers, although metabolic fractionation causes the values of consumer tissues to be 5 ‰ higher than those of plants (Caut et al. 2009). C_3 plants are the dominant species in the Maya lowlands, with $\delta^{13}C$ values –26.5 ‰ (O'Learly 1988), although local environmental conditions, such as the canopy effect, can cause these values to vary (Drucker et al. 2008; van der Merwe & Medina 1991). The most abundant C_4 plant consumed by the Maya was maize (*Zea mays*), with $\delta^{13}C$ values near –12.5 ‰ (O'Leary 1988; Smith and Epstein 1971). Although marine species also have elevated $\delta^{13}C$ values that overlap with the range of terrestrial C_4 plants in the Maya region (Keegan and DeNiro 1988; Rand et al. 2021a), it is unlikely they formed a significant part of the diet at the inland sites considered in this study.

Stable nitrogen isotope ($\delta^{15}N$) values increase stepwise by 3 to 5 ‰ at each level of the food chain (Delwiche and Steyn 1970; Hedges and Reynard 2007; O'Connell et al. 2012) and indicate the trophic level of consumers. Thus, human diets that included terrestrial animal protein will have elevated bone collagen $\delta^{15}N$ values relative to herbivores. This also allows breastfeeding infants to be identified as those with elevated $\delta^{15}N$ values relative to their mothers (Fuller et al. 2006). Terrestrial plants have $\delta^{15}N$ values around +3 ‰, although legumes that directly fix nitrogen have values close to 0 ‰ (Delwiche and Steyn 1970; Wada et al. 1975). Environmental factors such as precipitation, aridity, and soil nitrates (Ambrose 2001; Somerville et al. 2018) and cultural factors such as agricultural practices (Szpak 2014) can further influence human bone collagen $\delta^{15}N$ values. As with $\delta^{13}C$ values, the $\delta^{15}N$ values of marine species tend to overlap with those

of terrestrial species in the Maya region (Rand et al. 2021a; Sharpe et al. 2018; Thornton et al. 2016), although this is unlikely to be a concern in this study, as explained above. Finally, both the $\delta^{13}C$ and $\delta^{15}N$ values of freshwater species are not well known in the Maya region, but preliminary analyses suggest they are highly variable and reflect the diverse dietary preferences of freshwater species (Rand et al. 2021a).

Sulfur isotope values in archaeological skeletal tissues have been used to differentiate between the consumption of terrestrial, freshwater, and marine resources and can be useful for identifying nonlocal individuals in archaeological contexts (Nehlich 2015). Bone collagen $\delta^{34}S$ values are derived from dietary methionine, which is assimilated from environmental sulfur by plants at the base of the food chain (Brosnan and Brosnan 2006; Ingenbleek 2006). Because animals cannot synthesize this essential amino acid internally, it must be obtained from dietary protein (Brosnan and Brosnan 2006; Ingenbleek 2006; Tanz and Schmidt 2010). While the offset between the $\delta^{34}S$ values of consumer tissues and their diet ($\Delta^{34}S_{tissue\text{-}diet}$) is assumed to be below the level of analytical uncertainty and therefore inconsequential for dietary interpretation (i.e., +0.5 ± 2.4 ‰; Nehlich 2015:Table 2; see also Krajcarz et al. 2019), other research indicates it may be more substantial (i.e., –1.5 ‰; Webb et al. 2017; see also Tanz and Schmidt 2010). Culinary practices, such as the addition of salt or processing maize with lime (i.e., nixtamalization), may also complicate the interpretation of human $\delta^{34}S$ values. While these techniques may introduce exogenous sulfur to foods, this sulfur has not been assimilated into methionine by plants and therefore is not bioavailable for incorporation into consumer bone collagen. Nixtamalization does, however, double the amount of digestible methionine available from

maize (Ellwood et al. 2013; Katz et al. 1974), and so the δ^{34}S values of Maya bone collagen may be preferentially derived from processed maize over animal protein.

Marine sulfate has uniform δ^{34}S values around +21 ‰ (Böttcher et al. 2007; Rees et al. 1978), which is also deposited into coastal soils due to the sea spray effect (Gravenhorst 1978; Wakshal and Nielsen 1982). Freshwater rivers and lakes contribute lower δ^{34}S values to aquatic plants and their consumers in the Maya region, and the consumption of terrestrial animals from the granitic Mountain Pine Ridge of the Maya Mountains or volcanic Maya Highlands are also expected to contribute lower values to human tissues in these regions (Chapter 3; Rand et al. 2021a). Indeed, two humans from Peligroso and Ramonal in the Mountain Pine Ridge area both had δ^{34}S values of +8.5 ‰ (Ebert et al. under review). Although the Yucatan Peninsula exhibits higher δ^{34}S values than in other inland archaeological contexts due to the limestone geology, they vary depending on the age of formation and distance from the coast, permitting the identification of nonlocal individuals from isotopically distinct regions (Chapter 3; Rand et al. 2021a).

Finally, the residential history throughout an individual's life course may be reconstructed through a comparison of multiple isotopic assays of tissues that form at different ages. It is difficult to assess the influence of diagenesis on $^{87}Sr/^{86}Sr$ and δ^{18}O values and therefore enamel is preferentially sampled over bone, as it is less susceptible to diagenesis (Hoppe et al. 2003). Enamel forms during childhood and does not subsequently remodel (AlQahtani et al. 2010; Moradian-Oldak 2009), so that the $^{87}Sr/^{86}Sr$ and δ^{18}O values of enamel indicate the source of foods and water consumed during childhood. In contrast, because bone remodels throughout life, the δ^{34}S values of collagen will represent an average of dietary protein consumed from adolescence to the end of life, depending on

which bone is sampled and individual physiological variation in bone turnover rates (Hedges et al. 2007; Matsubayashi and Tayasu 2019; Parfitt 2001). Thus, a comparison of isotopic techniques applied to tissues from the same individual that form at different ages may therefore reveal whether her or she migrated multiple times as well as the length of time he or she resided in the place of burial prior to death.

4.2 Site and Sample Description

Samples of human bone from seven sites (Fig. 4.1), including Xunantunich (n = 11), San Lorenzo (n = 7), Pacbitun (n = 26), and Caledonia (n = 24) in western Belize, as well as Nakum (n = 9) and San Bernabé (n = 10) in Peten, Guatemala, and Calakmul (n = 10) in southern Campeche, Mexico were selected for analysis. Although nine bone samples from Chac in western Yucatan, Mexico, were also prepared, they were too poorly preserved for stable sulfur isotope analysis (Appendix E) and so this site is not discussed further. The remaining sites are described below, their chronologies are presented in Figure 4.2, and details regarding specific archaeological projects can be found in Appendix A. The samples from each site that provided sufficient collagen (i.e., at least 16 mg) for stable carbon, nitrogen, and sulfur isotope analyses (n = 49) are also summarised here and in Table 4.1, and the details of individual samples can be found in Appendix E.

4.2.1 Xunantunich and San Lorenzo, Belize

Xunantunich is one of the largest sites in the Belize Valley (see Figure 4.3), consisting of a core of four monumental groups (Groups A to D) that cover 0.14 km^2 on top of a hill east of the Mopan River. While there is evidence of a small Early and Middle Preclassic settlement at the site, Xunantunich was established as a major center at the

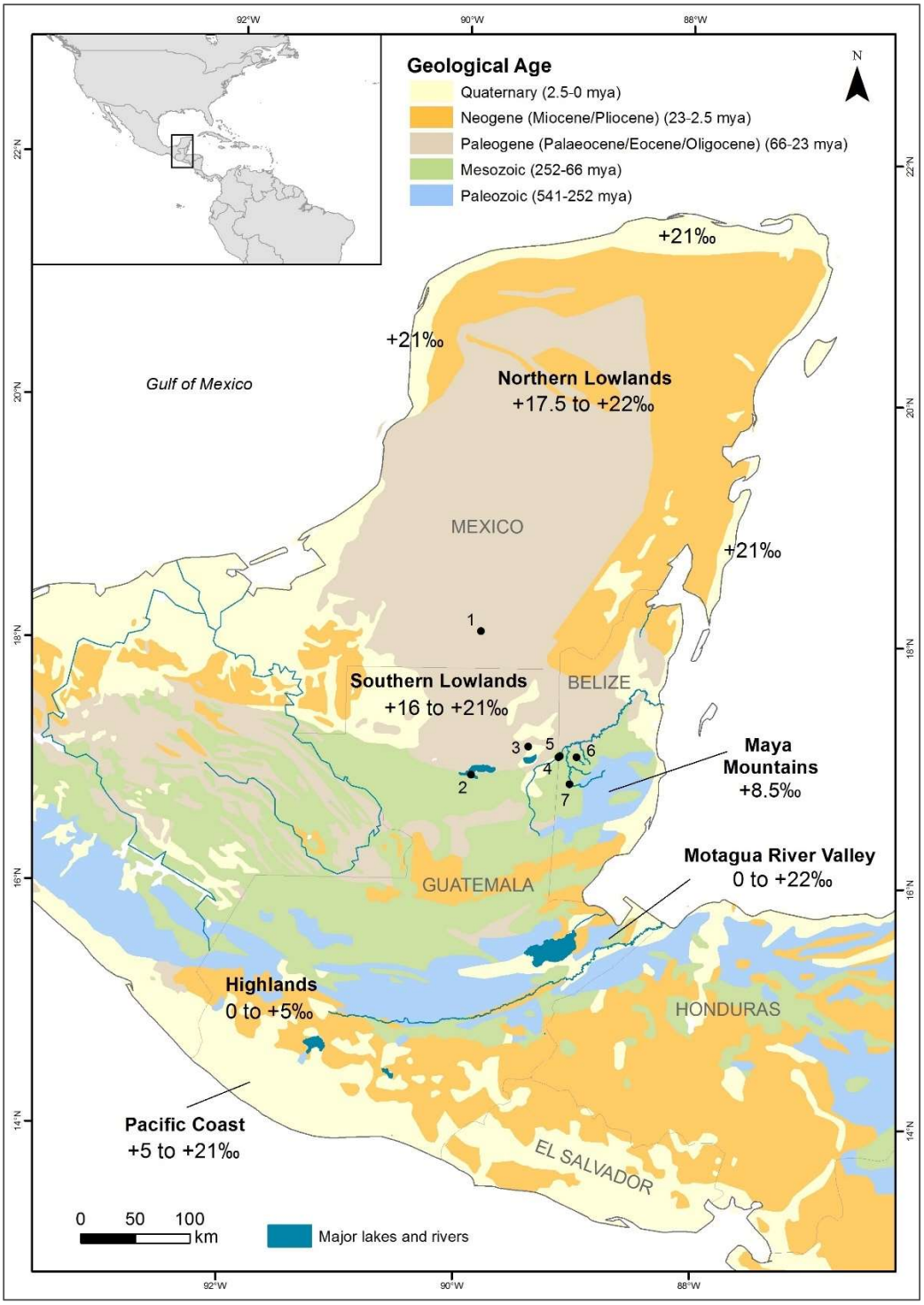

Figure 4.1: Geological baseline map of the Maya region indicating the expected environmental $\delta^{34}S$ values and location of Maya sites from which samples of human bone were analyzed: (1) Calakmul, (2) Mission San Bernabé, (3) Nakum, (4) Xunantunich, (5) San Lorenzo, (6) Pacbitun, (7) Caledonia, and (8) Chac. Map created by Bryn Trapper based on the Geological Map of North America 2005 (1:5,000,000) (Garrity and Soller 2009).

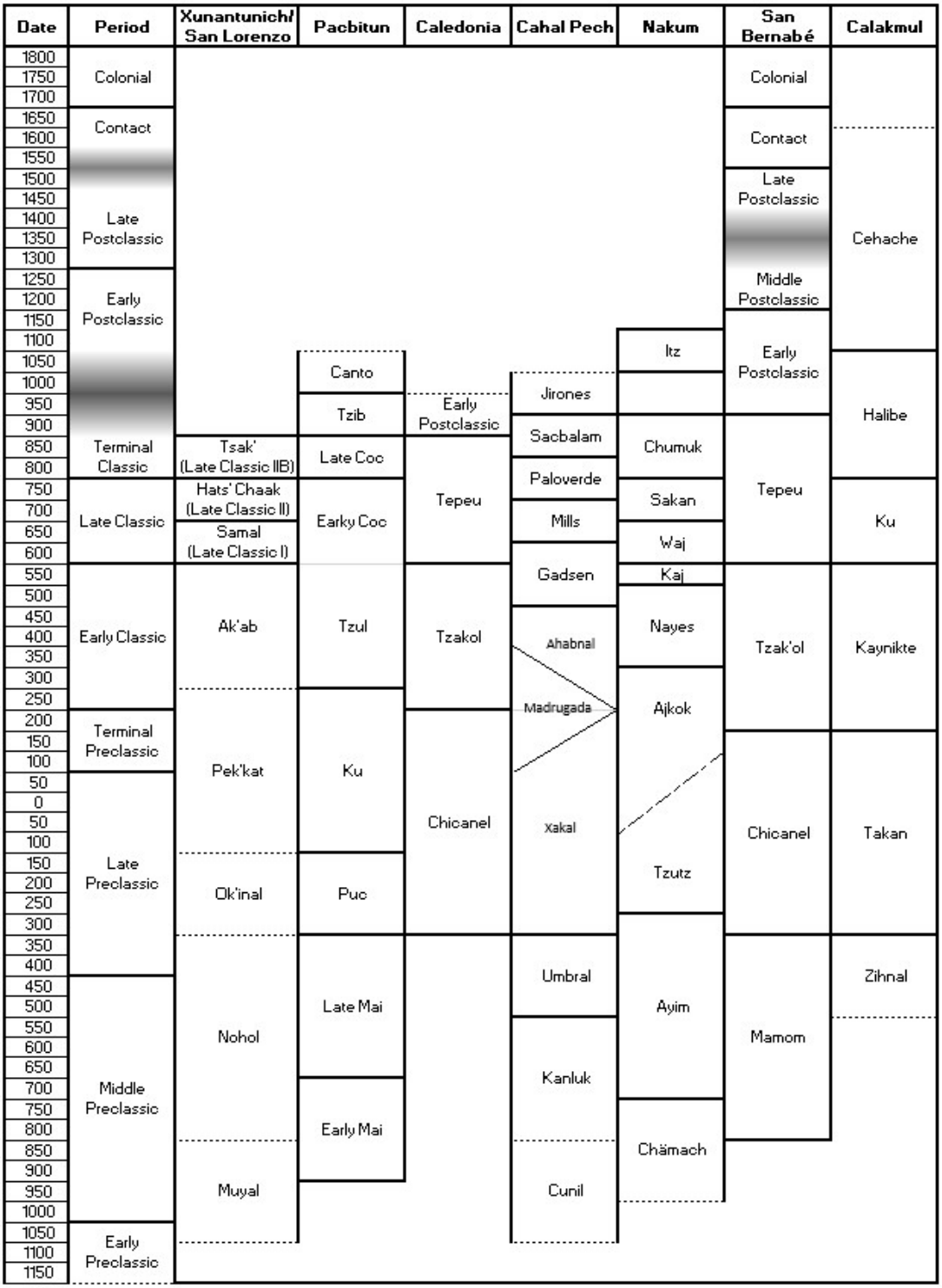

Figure 4.2: Chronological periods and ceramic phases of the sites discussed in the chapter. Note that the Uaxactun ceramic sequence was used at both Caledonia and Mission San Bernabé, and that the phases have been rounded to the nearest 50 years. Data compiled from Awe (1985), Domínguez Carrasco (1994), Folan et al. (1995), Healy et al. (2004a, 2004b), LeCount et al. (2002), Leventhal et al. (2010), Powis et al. (2017), Pugh et al. (2012), and Źrałka et al. (2018).

Table 4.1: Summary of the osteological and contextual data of the Maya human samples included in this study by site.

Site	N	Sex						Age			Context						Chronology									
		F	F?	I	M?	M	U	A	S	U	F	S	NF	C	R	U	PrC	EC	E-LC	LC	LC-TC	TC	TC - EPC	PA	Col	U
Xunantunich	6	1		2	1	2		6			4	1	1	2	4		1			2	2	1	1			
San Lorenzo	1	1						1			1				1					1						
Pacbitun	11	2	1	4		4		10	1		10	1		5	6					2		8		1		
Caledonia	18	1	1	14	1	1		17	1		17		1	18			1		6	11						
Nakum	5	1		4				4	1		2	1	2	5			2	1				2				
San Bernabé	8	2		1	1	4		7	1		8			8											8	
Calakmul	1						1			1						1										1
Total	50	8	2	25	3	11	1	45	4	1	42	3	4	38	11	1	4	1	6	16	2	11	1	1	8	1

Sex: F=female; F?=probable female; I=indeterminate; M?=probable male; M=male; U=unknown.
Age: A=adult (>20 years of age); S=Subadult (<20 years of age); U=unknown.
Context: F=funerary; S=sacrificial; NF=non-funerary; C=ceremonial; R=residential; U=unknown.
Chronology: PrC=Preclassic (Before 250 CE); EC=Early Classic (250-600 CE), E-LC=Early to Late Classic (500-675 CE); LC=Late Classic (600-800CE); TC=Terminal Classic (800-900/1100 CE); EPC=Early Postclassic (900/1100-1300 CE); PA=Post-Abandonment (after 900 CE); Col=Colonial (1697-1821 CE); U=unknown.

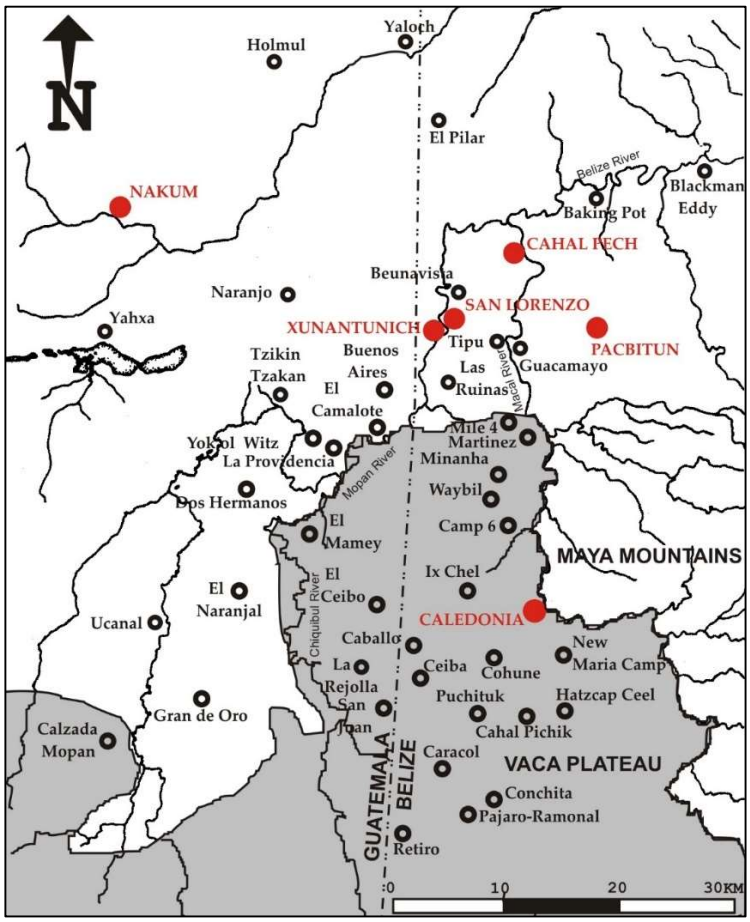

Figure 4.3: Map of eastern Peten, the Belize River Valley, the Vaca Plateau (shaded area), and Maya Mountains. Sites mentioned in the text are highlighted in red. Note: location of Mission San Bernabé, Chac II, and Calakmul not shown (modified from the original Social Archaeology Research Program (SARP) project map with permission from Dr. Gyles Iannone [personal communication, 2020]).

beginning of the Late Classic period around 600/670 CE (LeCount et al. 2002), likely through its mutual ties to Naranjo (LeCount and Yaeger 2010; LeCount et al. 2002; Leventhal et al. 2010). By the beginning of the Late Classic II phase (670-780 CE: see Fig. 4.2), the site had reached is peak in terms of population and architecture. With the fall of Naranjo around 820 CE, a new autonomous ruling family took charge at Xunantunich (LeCount and Yaeger 2010; Leventhal et al. 2010).

San Lorenzo was a small community located on a ridge approximately 1.6 km northeast of Xunantunich on the east bank of the Mopan River (Yaeger 2000). This community consisted of five spatially discrete settlement clusters, numerous isolated mounds, and a ritual-administrative group (SL-13). These structures primarily date to the Late and Terminal Classic periods (600-890 CE), although a community existed at the site in earlier periods (Yaeger 2000). This site has been interpreted as a rural community in the hinterland of Xunantunich with social and economic ties to the larger centre (Yaeger 2000). As at Xunantunich, it appears that occupation at San Lorenzo rapidly grew during the Late Classic I phase (600-670 CE), peaked during the Late Classic II phase, after which it experienced a decline and eventual abandonment in the Terminal Classic (Yaeger 2000).

Based on archaeological and isotopic evidence, the residents of Xunantunich and San Lorenzo likely obtained most subsistence resources locally, farming in the alluvial floodplain of the Mopan River and the limestone uplands and obtaining faunal resources from the uplands and the river (Fedick 1995; Yaeger 2010:234). The river also facilitated trade and travel (LeCount and Yaeger 2010; Yaeger 2005:5, 2010). Indeed, isotopic analysis found that animal resources were brought to the site from the Vaca Plateau and Macal River regions to the south and east (Yaeger and Freiwald 2009), and that 50% of sampled individuals from Xunantunich and 30% from San Lorenzo were born in isotopically distinct regions (Freiwald 2011a, 2011b; Freiwald et al. 2014), perhaps reflecting rapid site growth in the Late Classic period (Whitridge, personal communication, 2021).

Because San Lorenzo is a hinterland community of Xunantunich, their data sets have been combined in this study. A total of 6 adult individuals from Xunantunich and 1

from San Lorenzo are considered in this study, including two females, two males, one probable male, and two individuals of indeterminate sex. Five came from formal funerary contexts, one came from a termination deposit, and one was from a non-funerary context. Two of these individuals were interred in ceremonial structures and five in residential complexes. Finally, one dates to the Late Preclassic, two dates to the Late Classic II period, two date to the Late Classic II or Terminal Classic periods, one dates to the Terminal Classic, and one dates to the Terminal Classic or Early Postclassic period (see Table 4.1 and Appendix E).

4.2.2 Pacbitun, Belize

Pacbitun is a medium-sized regional centre located in the limestone foothills 1 km to the north of the Maya Mountains (Figs. 4.1 and 4.3). The site epicenter comprises five primary plaza groups (A to E) with a total of 40 major masonry structures (Healy et al. 2004b, 2007), and is part of the broader core zone that contains numerous small and medium-sized structures likely representing commoner households (Healy et al. 2004b, 2007). Pacbitun was occupied from the Middle Preclassic (~900 BCE) to the end of the Classic period. During the Early Classic period, the site may have been politically linked with Caracol on the Vaca Plateau, although most of the material culture from Pacbitun in the Late Classic is more similar to that from Xunantunich (Healy et al. 2004b). During the Late and Terminal Classic periods (550-900 CE), population and monumental construction at Pacbitun reached their florescence before the site was abandoned around 900 CE, although there is also at least one post-abandonment burial from the site (Healy et al. 2004b, 2007).

The location of the site near the intersection of the tropical broadleaf rainforest and the Mountain Pine Ridge region of the Maya Mountains provided access to numerous resources, fertile agricultural land, as well as various animal species for local use or export (Emery and Healy 2014; Healy 1990). Archaeological evidence also indicates that long-distance trade networks were established by about 500 BCE (Awe and Healy 1994). Due to population increase during the Late Classic period, agricultural terraces were built in the limestone hills to increase agricultural production (Healy et al. 1980). Indeed, stable carbon and nitrogen isotope analysis of twenty burials from Pacbitun revealed that maize consumption increased during the Early and Late Classic periods and decreased during the Terminal Classic (Coyston et al. 1999; White et al. 1993).

Eleven Pacbitun individuals were analyzed in this study. One was a subadult and ten were adults, including two females, one probable female, four males, and three individuals of indeterminate sex. The five formal burials from four funerary and one dedicatory deposit interred in ceremonial architecture in the epicentre are presumed to be of higher status than the six formal burials from residential contexts in the core zone (Robertson 2011). Eight date to the Terminal Classic period, whereas two date to the Early Classic period, and one was buried after the site was abandoned (Table 4.1; Appendix E).

4.2.3 Caledonia, Cayo District, Belize

Caledonia was a minor Maya centre located on the west bank of the Macal River at the intersection of the limestone Vaca Plateau and metamorphic Pine Ridge region of the Cayo District in Belize (Figs. 4.1 and 4.3). The site consists of four plazas arranged into two groups located on slight hills separated by a creek (Awe 1985). Although Caledonia

was first settled during the Preclassic period around 100 CE and continuously occupied, it primarily dates to the second half of the Classic period (600-1000 CE; Awe 1985:388) and was abandoned in the Terminal Classic or Early Postclassic periods (900-1000 CE). Caledonia was likely under the influence, if not actual control, of a larger primary centre, most likely nearby Caracol (Awe 1985). Based on the ceramic assemblage, Awe (1985) proposed that Caledonia, through Caracol, was influenced by sites located in the central Peten until the early Late Classic period, after which some influence appears to have come from the Belize Valley before the site was again affiliated with those in Peten.

Previous carbon and nitrogen isotope analyses found these individuals consumed a maize-based diet with contributions from C_3 plants and terrestrial herbivores, and possibly freshwater snails and/or molluscs (Rand 2012; Rand et al. 2015b). While stable oxygen isotope analysis indicates all individuals were local, the elevated values from the six individuals interred in Burial 1 suggest they may have relied on a different source of drinking water or moved from a nearby area, as did one individual from Burial 3 who had enamel and bone values that differed from those oft the other three individuals from this burial (Rand 2017). This dissertation research builds upon preliminary sulfur isotope results that suggest these individuals obtained their protein locally, although variation was present (Rand and Grimes 2017).

Eighteen individuals from Caledonia were analyzed in this study, including one female, one probable female, thirteen individuals of indeterminate sex, one probable male, and one male, all of whom were adults. An additional subadult could not be sexed. All were from funerary contexts in ceremonial architecture in the site core, excluding an adult third metatarsal recovered from within Vessel 3 in Burial 1. While I have interpreted the latter

as a “finger bowl”, it is unlike finger bowls from non-funerary caches at nearby Caracol that consist of small unslipped dishes set lip-to-lip containing metacarpals or phalanges of the hand (Chase and Chase 2017:213). One individual dates to the Preclassic period, six date to the transition between the Early and Late Classic periods, and the remaining 11 individuals date to the Late Classic period (Table 4.1; Appendix E).

4.2.4 Nakum, Guatemala

Nakum is located on the bank of the Holmul River in Peten region of Guatemala (Fig. 4.1 and 4.3). The site is divided into a Northern and Southern Sector that are connected by the Perigny Causeway (Źrałka and Hermes 2012). Nakum was continuously occupied from the Middle Preclassic through to the Terminal Classic period, and following a brief hiatus, there is some evidence for Postclassic occupation at the site (Koszkul et al. 2006, 2009; Źrałka and Hermes 2012; Źrałka and Koszkul 2007; Źrałka et al. 2014, 2017, 2018). Throughout the Late Classic period, Nakum was likely subordinate to Tikal or Naranjo, although the decline of these centres during the Terminal Classic allowed Nakum to experience architectural and political growth, and possibly the arrival of migrants from surrounding sites, until the site was ultimately abandoned around 950 CE (Źrałka and Hermes 2012).

The Holmul River was an important trade route between the Caribbean and Central Peten and was likely intermittently controlled by Tikal and Naranjo prior to their decline during the Terminal Classic, when individuals from Nakum took control of the trade route (Źrałka and Hermes 2012:178). The location on the river would have facilitated the transport of goods, foodstuffs, and people to and from Nakum. The subsistence base for the

population of Nakum was probably facilitated by agriculture in fields underlain by Palaeogene and Quaternary limestones and animals hunted in the surrounding region, although at least one deer was brought to the site, perhaps from the Maya Mountains (Rand et al. 2020a, 2021a; Chapters 3 and 5).

Five Nakum individuals provided sufficient collagen for analysis, including one adult female and three adults of indeterminate sex, and one subadult who could not be sexed. All five came from ceremonial structures in the site core, two of which were formal funerary contexts, one was interpreted as a termination deposit, and two were non-funerary in nature. Finally, two individuals date to the Preclassic period, one dates to the Early Classic, and two date to the Terminal Classic period (Table 4.1; Appendix E).

4.2.5 Mission San Bernabé, Guatemala

Unlike the other sites included in this study, Mission San Bernabé was a Colonial period Spanish mission established near the Postclassic Itza Maya site of Tayasal on Lake Peten Itza in central Peten, Guatemala (Fig. 4.1). Following their defeat of the Itza in 1697 CE, the Spaniards built a *presidio* (fortified administrative centre) on the ruins of the Itza capital of Nojpeten on Flores Island (Jones 1998) and forcibly relocated Maya populations to *reducciones* around Lake Peten Itza (Jones 1998; Pugh et al. 2012, 2016; Schwartz 1990). Mission San Bernabé was one such *reduccion* built by at least 1712 CE on a Late Preclassic site close to Tayasal that was intensively reused during the Late to Terminal Classic periods (Pugh et al. 2012). However, by 1778 CE, the site was abandoned (Caso Barrera 2002:352 Table VII.1; Jones 1998: Table 15.4).

In terms of subsistence, historical documents suggest the Spaniards encouraged

Peten Maya to cultivate maize and beans and discouraged them from relying on forest and garden resources (Schwartz 1990:48-49, 62). Although deer, peccary, and turtles were important in earlier periods, Colonial Mission San Bernabé residents preferred cows and pigs, although aquatic species remained important (Freiwald 2012, n.d.; Freiwald and Pugh 2018; Pugh et al. 2016). Isotopic analyses suggest that European domesticates were raised locally but were likely foddered in different ways (Freiwald under review; Freiwald and Pugh 2018). Strontium and stable oxygen isotope analysis also suggest that most of the residents of Mission San Bernabé were local and probably Maya (Freiwald et al. 2020), although people of Spanish and African descent also likely lived in settlements around the lake (Pugh et al. 2012).

Eight individuals interred in the church of Mission San Bernabé were analyzed in the current study, including a subadult, two adult females, four adult males, and one adult who was probably male. All were interred in Christian style burials within and to the east of the Mission San Bernabé church during the Colonial period (Table 4.1; Appendix E).

4.2.6 Calakmul, Mexico

Calakmul is located in the southeastern part of Campeche, Mexico (Fig. 4.1) on a 35 m rise east of a large *bajo* (seasonal swamp). The core area comprises 975 structures within 1.75 km^2, while smaller residential mounds extend for an additional 20 km^2 from the site core (Folan et al. 1995; Martin and Grube 2008; Sharer and Traxler 2006:356). Calakmul was likely established during the Middle Preclassic but rose to prominence as a large civic-ceremonial centre in the Late Preclassic period. The fall of nearby El Mirador in the Late Preclassic was likely a turning point for Calakmul, and by the Early Classic the

site had emerged as a powerful regional capital. Throughout the Early Classic, Calakmul was at the centre of regional politics in the lowlands, competing with Tikal for alliances with sites such as Yaxchilan, Caracol, and Naranjo (Folan et al. 1995; Martin and Grube 2008). At the beginning of the Late Classic period, the Kaanul dynasty moved from the site of Dzibanche to Calakmul (Martin 2020:391), transforming the site into one of the most important centres in the lowland Maya region, with a regional state covering at least 80,000 km^2 that included numerous secondary centres. The site continued to be occupied into the Terminal Classic period and the last datable stela from Calakmul was dedicated in 810 CE prior to the abandonment of the site (Folan et al. 1995).

Archaeological evidence indicates that the rich soils along the margin of the bajo were used for agriculture following droughts that dropped the water level after 200 CE (Domínguez Carrasco and Folan 1996). Due to the location of Calakmul in an area with limited surface water, residents relied on complex hydraulics to irrigate agricultural fields and trade to obtain additional subsistence resources and raw materials (Gunn et al. 2002). Previous isotope analysis found that the Calakmul individuals consumed a typical Classic Maya maize-based diet supplemented with other plant and animal resources, and that over two thirds of the population was local (Price et al. 2018a). Ten human bone samples were prepared for analysis, although only one sample from an individual of unknown age and sex (F5335; Ent. 2 Caja 10) was sufficiently preserved for isotopic analyses in this study (Appendix E).

4.3 Methods

Originally, 106 human bone samples were prepared for stable isotopic analyses,

including 11 from Xunantunich, 7 from San Lorenzo, 26 from Pacbitun, 24 from Caledonia, 9 from Nakum, 10 from Mission San Bernabé, 10 from Calakmul, and 9 from Chac II (Appendix E)[9]. Samples were cleaned, prepared, and analyzed using the same methods applied to the faunal remains in Chapter 3 and described in detail in Appendix A. Briefly, a modified Longin (1971) method was used to extract collagen, wherein samples were first demineralized in hydrochloric acid (0.5 M HCl) and treated with sodium hydroxide (0.1 M NaOH; excluding the initial Caledonia samples, see Appendix A and B for details) prior to being hydrolysed, ultrafiltered, and freeze-dried (Honch et al. 2006; Nehlich and Richards 2009; Szpak et al. 2017b).

Collagen was successfully extracted from 70 of the 106 samples (Appendix E), which is unsurprising given that Maya skeletal samples are often poorly preserved. All 70 samples were subjected to stable carbon and nitrogen isotope analysis because of the low amount of collagen (1 mg) required for these analyses, but also because these data are necessary to evaluate whether the δ^{34}S values have been influenced by diagenesis (Nehlich and Richards 2009) and to interpret the δ^{34}S results. Unlike stable carbon and nitrogen isotope analysis, stable sulfur isotope analysis requires larger collagen samples (5 to 50 mg depending on the laboratory; Appendix A), and only 56 of the 70 samples yielded sufficient collagen for this procedure.

Carbon and nitrogen isotopes and concentrations from the Caledonia, Pacbitun, and Nakum samples were analyzed in CREAIT's Stable Isotope Laboratory at Memorial

[9] Sample selection was determined by the principal investigators of individual archaeological projects and were largely chosen to address research questions specific to each project. Poor bone preservation typical of the Maya region also dictated which burials and elements were included in this study. These factors combined influenced the final number of samples included in this study.

University (MUN; see Appendix A for details) with a standard uncertainty of ±0.28 ‰ for $\delta^{13}C$ and ±0.24 ‰ for $\delta^{15}N$ (Appendix C). Samples from Caledonia were also analyzed in the Ján Veizer Stable Isotope Laboratory at the University of Ottawa (Ottawa), as were samples from San Lorenzo, Xunantunich, Mission San Bernabé, Chac II, and Calakmul (see Appendix A) with a standard uncertainty of ±0.11 ‰ for $\delta^{13}C$ and ±0.08 ‰ for $\delta^{15}N$ (Appendix C).

The stable sulfur isotopes and concentrations from the original Caledonia samples prepared without a NaOH step were also analyzed at MUN (see Appendix A) with a standard uncertainty of ±1.24 ‰ for $\delta^{34}S$ (Appendix C). The original samples and resamples from Caledonia, as well as the samples from Pacbitun and Nakum were analyzed by the Stable Isotope Laboratory in the Department of Earth and Planetary Sciences at the University of Tennessee (Tennessee; Appendices A and B). Measurement precision was ±1.00 ‰ for $\delta^{34}S$, although analytical accuracy and standard uncertainty could not be assessed as check standards were not included in the analyses (Appendix C). Finally, one sample from Caledonia, as well as the samples from Xunantunich, San Lorenzo, Mission San Bernabé, and Calakmul were analyzed at Ottawa (Appendix A) with a standard uncertainty of ±0.32 ‰ for $\delta^{34}S$ (Appendix C).

Stable sulfur isotope analysis can identify nonlocal individuals as those with $\delta^{34}S$ values that differ from those expected from locally available sources of protein. While faunal baselines are useful for approximating local $\delta^{34}S$ values (Chapter 3), faunal remains were not available from all seven sites from which human remains were analyzed. Instead, outliers were identified as those with $\delta^{34}S$ values that fell beyond the interquartile range (IQR) multiplied by 1.5 subtracted from the first quartile and added to the third quartile of

the data set from each site (see Appendix A). These outlying δ^{34}S values were then removed, and the local range of δ^{34}S values was calculated as falling within two standard deviations of the mean ($\bar{x} \pm 2\sigma$) of the remaining values (after Price et al. 2002; see Appendix A). The distribution of the δ^{13}C, δ^{14}N, and δ^{34}S values by site were assessed using the Shapiro-Wilk test (W), and appropriate comparative statistical methods were then applied to explore correlations and differences within, between, and among the data sets (Appendix A). All statistical analyses were performed in SPSS version 25 for Windows (IBM®) and the results were considered statistically significant when $p < 0.05$.

4.4 Results

Forty-nine samples provided sufficiently preserved collagen for stable carbon, nitrogen, and sulfur isotope analysis. Following a short description of data comparability among laboratories and the removal of diagenetically altered samples, the isotopic values of the remaining samples from each site are described and statistically compared with an emphasis on the stable sulfur isotope results.

4.4.1 Data Comparability

Although the interlaboratory variability of δ^{13}C, δ^{15}N, %C and %N is considered negligible (Pestle et al. 2014), the comparability of the δ^{34}S and %S values of sample aliquots analyzed by different laboratories has yet to be evaluated. Preliminary comparisons of the Caledonia bone collagen samples analyzed at both MUN and Tennessee found no statistically significant differences in the δ^{34}S and %S values ($W = -0.85$, $p = 0.40$ and $W = -0.65$, $p = 0.51$, respectively; Appendix B). Only one sample (Caledonia Burial 1 Vessel 3, Lab # 4406) was analyzed at both Tennessee and Ottawa, and the difference in the δ^{34}S

values of this sample obtained from these laboratories (+2.52 ‰) exceeded that of the average pairwise difference between samples analyzed at MUN and Tennessee (+0.23 ± 0.93 ‰; Appendix B) as well as the analytical uncertainty determined for all three laboratories (Appendix C). Unfortunately, this comparison is based on a single sample and cannot be used to represent the true variability in isotopic measurements between these laboratories. Therefore, although the stable carbon, nitrogen, and sulfur isotope results obtained from MUN, Tennessee, and Ottawa are compared in this study, the results and interpretations presented here may change as understandings of interlaboratory comparability of sulfur isotope results develop further.

4.4.2 Sample Integrity

Diagenesis was assessed using established criteria, including wt. %C, wt. %N, wt. %S, C:N, C:S, and N:S (Ambrose 1990; DeNiro 1985; Nehlich and Richards 2009; van Klinken 1999; see Appendix A). Excluding three samples that had C:N values above 3.6 DeNiro 1985), all other diagenetic indicators of the remaining 67 collagen samples subjected to stable carbon and nitrogen isotope analyses fell within acceptable parameters and were deemed sufficiently preserved for interpretation (Appendix E). Fifty-six collagen samples were large enough for sulfur isotope analysis, one of which was excluded from interpretation because it had a C:S value above 900 (Nehlich and Richards 2009). Two additional samples were excluded because they were not subjected to stable carbon and nitrogen isotope analysis and therefore could not be diagenetically evaluated (Appendix E). Finally, the isotopic values of four mandibles from Caledonia are presented in Appendix E but were removed from the statistical calculations and interpretation because they likely

each belonged to one of the seven right fibulae from the same context; thus, four of the individuals in this burial may have been sampled twice. After removing the diagenetically altered samples and those potentially sampled multiple times, the $\delta^{34}S$, $\delta^{13}C$, and $\delta^{15}N$ values from a total of 49 human bone collagen samples from seven sites are evaluated in this study.

4.4.3 Isotopic Results

The Maya included in this study consumed a maize-based diet supplemented with other plants and animal protein, as evidenced by the stable carbon and nitrogen isotope results from the 49 human bone collagen samples analyzed here. The human $\delta^{13}C$ values ranged from –14.2 to –7.5 ‰ (Appendix E; Fig. 4.4) and were elevated relative to most of the terrestrial fauna samples discussed in Chapter 3 (Rand et al. 2021a.; Fig. 4.4), excluding

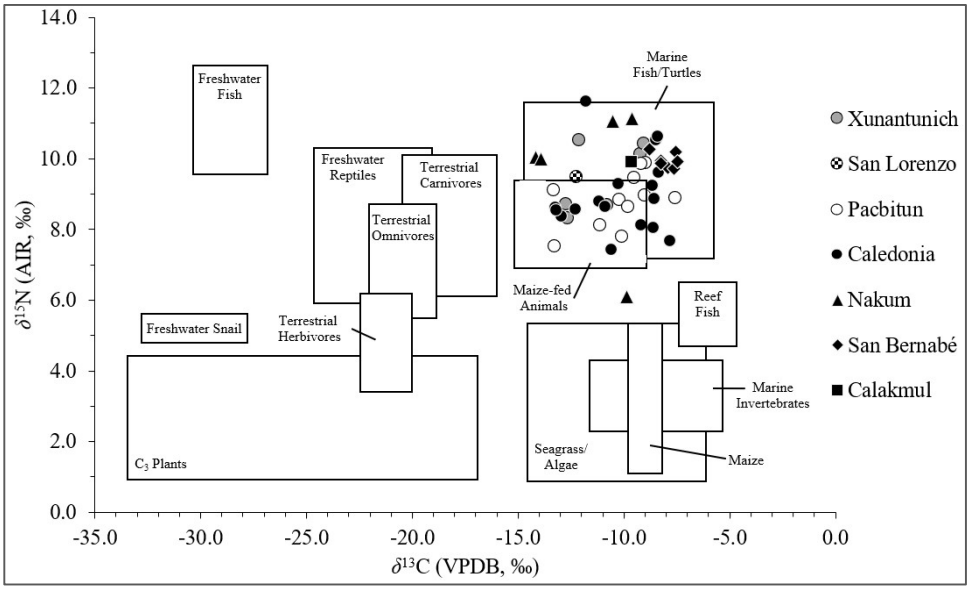

Figure 4.4: Human $\delta^{13}C$ and $\delta^{15}N$ values plotted against the food web presented in Figure 3.2 modified to include the faunal $\delta^{13}C$ and $\delta^{15}N$ values from this study (see Appendix D for individual faunal isotope values). Boxes represent the average and one standard deviation for each group of food resources, and the human values from each site have been individually plotted. Note that human $\delta^{13}C$ and $\delta^{15}N$ values have not been adjusted to account for trophic level offsets.

several dogs and turkeys that likely consumed maize. The human δ^{15}N values from these 49 samples ranged from +6.1 to +11.6 ‰ (Appendix E) and were also elevated relative to most of the faunal samples (Fig. 4.4), indicating the consumption of animal protein. Interestingly, the δ^{13}C and δ^{15}N values from the San Bernabé individuals were much more elevated and homogenous than those from prehispanic Maya sites (Table 4.2). A Kruskal-Wallis test found both the δ^{13}C values ($H(4) = 16.822$, $p = 0.002$) and δ^{15}N values ($H(4) = 13.634$, $p = 0.009$) to be significantly different among sites. Post hoc tests found individuals

Table 4.2: Summary statistics of the human δ^{13}C, δ^{15}N, and δ^{34}S values by site.

Site	n	Min	Max	Median	IQR	$\bar{x}$	σ
δ^{13}C (VPDB, ‰)							
Xunantunich/San Lorenzo	7	–12.7	–9.1	–12.1	2.4	–11.2	1.6
Pacbitun	11	–13.3	–7.5	–9.8	1.6	–10.2	1.8
Caledonia	18	–13.2	–7.9	–9.7	3.3	–10.1	1.9
Nakum	5	–14.2	–9.6	–10.5	4.0	–11.6	2.2
Mission San Bernabé	7	–8.8	–7.5	–7.9	0.7	–8.0	0.5
Calakmul	1			–9.6		–9.6	
δ^{15}N (AIR, ‰)							
Xunantunich/San Lorenzo	7	+8.3	+10.5	+9.5	1.6	+9.5	0.9
Pacbitun	11	+7.5	+9.8	+8.9	0.9	+8.8	0.8
Caledonia	18	+7.0	+11.6	+8.7	0.9	+9.0	1.1
Nakum	5	+6.1	+11.1	+10.0	1.1	+9.7	2.1
Mission San Bernabé	7	+9.7	+10.3	+9.9	0.3	+10.0	0.3
Calakmul	1			+9.9		+9.9	
δ^{34}S (VCDT, ‰)							
Xunantunich/San Lorenzo All	7	+13.3	+16.2	+13.7	0.7	+14.1	1.0
Xunantunich/San Lorenzo Outliers removed	6	+13.3	+14.3	+13.7	0.5	+13.8	0.4
Pacbitun All	11	+11.5	+14.7	+12.5	1.1	+12.7	0.9
Pacbitun Outliers Removed	10	+11.5	+13.6	-12.4	0.9	+12.5	0.7
Caledonia All	18	+7.9	+15.9	+11.1	2.2	+11.0	2.0
Caledonia Outliers Removed	17	+7.9	+13.4	+11.0	2.1	+10.7	1.6
Nakum	5	+12.9	+13.4	+13.1	0.4	+13.1	0.2
Mission San Bernabé	7	+14.6	+15.8	+15.3	0.5	+15.1	0.4
Calakmul	1			+17.4		+17.4	

Note: All values are in ‰ excluding n.

from the prehispanic sites had statistically similar $\delta^{13}C$ and $\delta^{15}N$ values (Tables 4.3 and 4.4). However, the San Bernabé individuals had significantly higher $\delta^{13}C$ values than those from Nakum (p = 0.007) and Xunantunich/San Lorenzo (p = 0.004), and the difference between the San Bernabé and Caledonia $\delta^{13}C$ values approached significance (p = 0.051; Table 4.3). The $\delta^{15}N$ values of the individuals from San Bernabé were also significantly higher than those from Caledonia (p = 0.023; Table 4.4).

The stable sulfur isotopes were also variable both among and within sites. Overall, the human $\delta^{34}S$ values ranged from +7.9 to +17.8 ‰ (Appendix E; Table 4.2; Fig. 4.5), which reflects the variability of environmental $\delta^{34}S$ values throughout the Maya region established in Chapter 3. However, it is necessary to identify and remove nonlocal individuals from the data set before the baseline values from each site may be compared. As illustrated in Figure 4.6, two nonlocal individuals with elevated $\delta^{34}S$ values

Table 4.3: Significance (p-value) of the post hoc pairwise comparisons of the Kruskal-Wallis test of the $\delta^{13}C$ values among sites.

Site	Nakum	Pacbitun	Mission San Bernabé	Xunantunich/ San Lorenzo
Caledonia	1.000	1.000	0.051	1.000
Nakum		1.000	**0.007**	1.000
Pacbitun			0.131	1.000
Mission San Bernabé				**0.004**

Note: Bolded values represent significant differences at the α=0.05 level.

Table 4.4: Significance (p-value) of the post hoc pairwise comparisons of the Kruskal-Wallis test of the $\delta^{15}N$ values among sites.

Site	Nakum	Pacbitun	Mission San Bernabé	Xunantunich/ San Lorenzo
Caledonia	0.148	1.000	**0.023**	1.000
Nakum		0.474	1.000	1.000
Pacbitun			0.133	1.000
Mission San Bernabé				1.000

Note: Bolded values represent significant differences at the α=0.05 level.

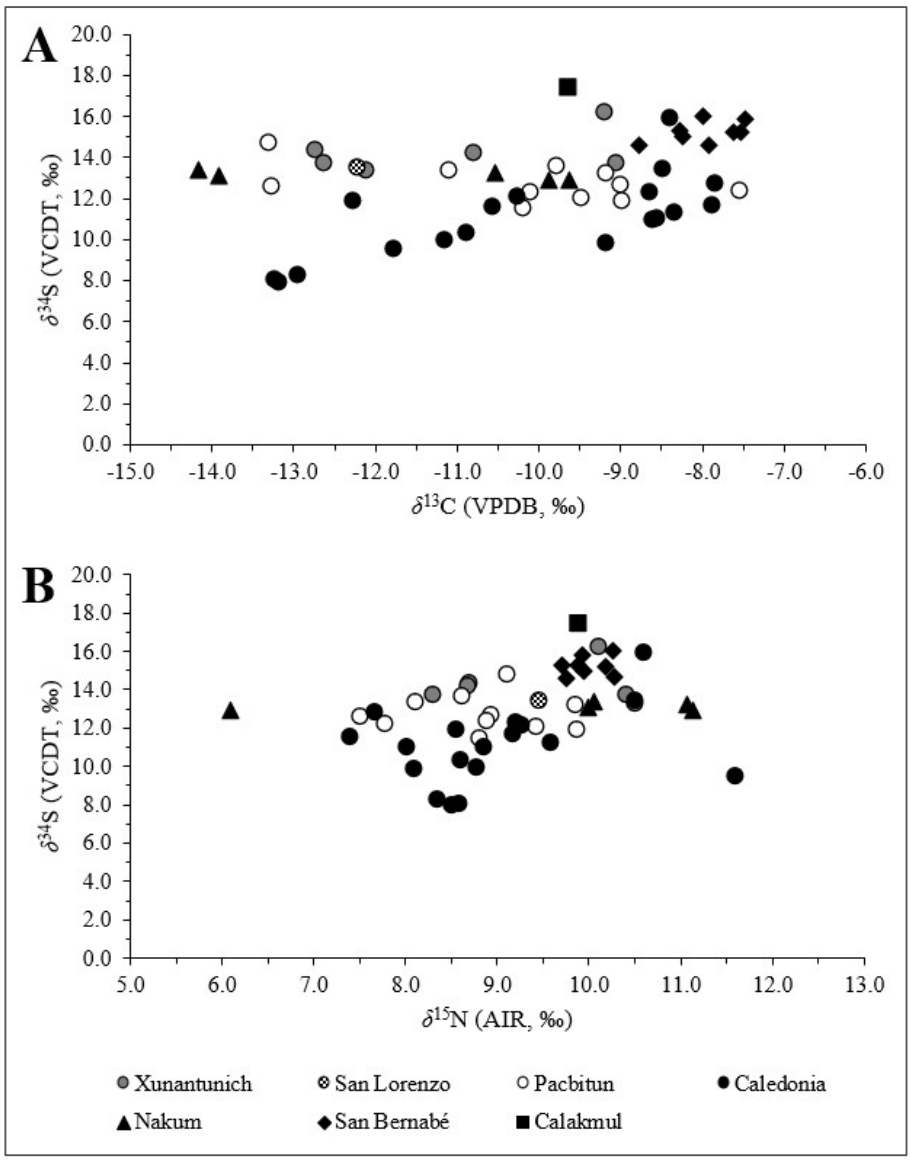

Figure 4.5: Human $\delta^{34}S$ values compared to (A) $\delta^{13}C$ and (B) $\delta^{15}N$ values for each site.

are evident in the Xunantunich/San Lorenzo and Caledonia data sets. When the Pacbitun $\delta^{34}S$ data set is separated by burial location in either the epicentre or core zone, a third nonlocal individual is visible as having an elevated value relative to others in the epicentre (Fig. 4.7).

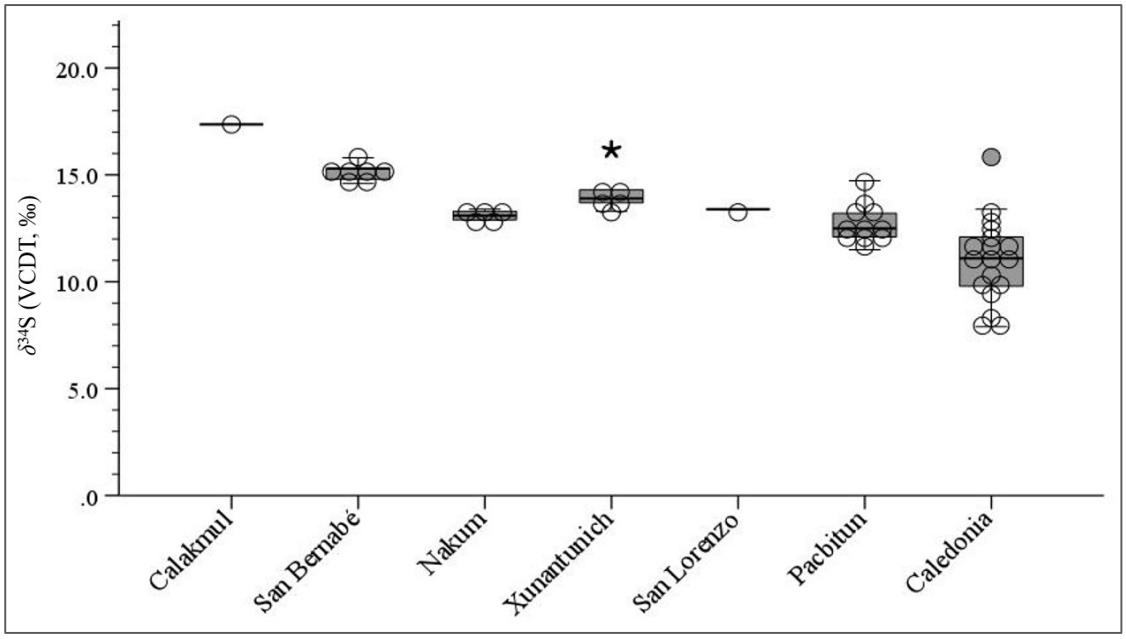

Figure 4.6: Boxplots of the human $\delta^{34}S$ values. Boxes represent the interquartile range (IQR), black bars represent the median, and whiskers represent the IQR*1.5 subtracted from the first quartile and added to the third. Transparent circles within the boxes and whiskers represent individual data points, filled circles beyond the whiskers represent outliers that fall beyond the IQR*1.5 subtracted from the first quartile or added to the third, and stars represent extreme outliers that fall beyond the IQR*3 subtracted from the first quartile or added to the third.

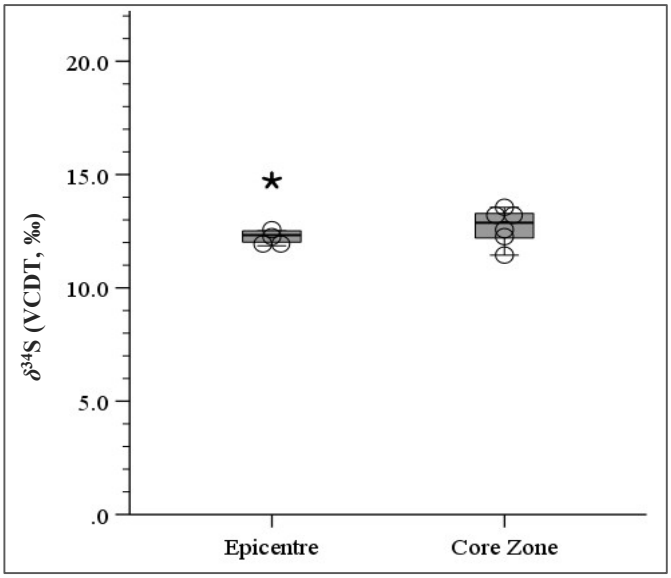

Figure 4.7: Boxplot of the $\delta^{34}S$ values of the Epicentre and Core Zone Burials from Pacbitun. Boxes represent the interquartile range (IQR), black bars represent the median, and whiskers represent the IQR*1.5 subtracted from the first quartile and added to the third. Transparent circles within the boxes and whiskers represent individual data points and stars represent extreme outliers that fall beyond the IQR*3 subtracted from the first quartile or added to the third.

The subdivision of the Caledonia $\delta^{34}S$ values by burial type identified no further outlying values, and the remaining data sets were statistically too small to assess differences in $\delta^{34}S$ values by age, sex, social status, burial location, or chronology. Thus, a total of three nonlocal individuals were identified in this study, indicating that between 5.6 and 14.3 % of the population migrated to their place of burial later in their lives (Table 4.5).

As with the faunal data presented in Chapter 3, the local ranges of human $\delta^{34}S$ values (Table 4.6) varied among sites. While many of the ranges overlapped, particularly those from sites in western Belize and Nakum, an ANOVA found the $\delta^{34}S$ values to be statistically different among sites ($F(4, 39) = 21.911$, $p < 0.000$). The $\delta^{34}S$ values from Caledonia were significantly lower than those from all other sites, while those from Mission San Bernabé were significantly higher (Table 4.7). The $\delta^{34}S$ values from the Xunantunich/ San Lorenzo individuals were also significantly higher than those from Pacbitun, but not Nakum, and the $\delta^{34}S$ values of individuals from Pacbitun and Nakum were also not significantly different from one another (Table 4.7).

It also appears that, like the faunal values, the human $\delta^{34}S$ values are dependent upon the underlying geology. Individuals from sites underlain by Paleogene/Neogene

Table 4.5: Number of individuals with nonlocal $\delta^{34}S$ values from the sites included in this study.

Site	# Nonlocal $\delta^{34}S$ Values	# Samples	%
Xunantunich/San Lorenzo	1	7	14.3
Pacbitun	1	11	9.1
Caledonia	1	18	5.6
Nakum	0	5	0.0
Mission San Bernabé	0	7	0.0
Calakmul[1]	?	1	?

[1]Calakmul is represented by a single sample so it is not possible to evaluate whether this sample truly represents the local $\delta^{34}S$ values for the site or whether it is an outlier if additional samples were to be analyzed.

Table 4.6: Local ranges of $\delta^{34}S$ values for sites included in the study determined as falling within two standard deviations of the mean when the outlying values from Xunantunich/San Lorenzo, Pacbitun, and Caledonia are removed.

Site	$\delta^{34}S$ Range (‰)[1]	*N*
Xunantunich/San Lorenzo	+13.0 to +14.6	6
Pacbitun	+11.1 to +13.9	10
Caledonia	+7.5 to +13.9	17
Nakum	+12.7 to +13.5	5
Mission San Bernabé	+14.3 to +15.9	7
Calakmul	+17.4	1

[1]The range is presented as two standard deviations of the mean rather than using the IQR method for consistency with ranges presented in other isotopic studies in the Maya region (see Methods for details).

Table 4.7: Significance (*p*-value) of the Games-Howell* post hoc evaluation of the one-way ANOVA of the $\delta^{34}S$ values among sites.

Site	Nakum	Pacbitun	Mission San Bernabé	Xunantunich/ San Lorenzo
Caledonia	**0.000**	**0.011**	**0.000**	**0.000**
Nakum		0.119	**0.000**	0.057
Pacbitun			**0.000**	**0.002**
Mission San Bernabé				**0.001**

Note: Bolded values represent significant differences at the α=0.05 level.
*The Games-Howell post hoc test was used because Levene's test indicated unequal variances ($F = 6.232$, $p = 0.001$).

limestone (Calakmul, Nakum, Mission San Bernabé) exhibit significantly higher $\delta^{34}S$ values ($U = 385.80$, $p = 0.000$) than those from sites situated on Mesozoic limestone (Caledonia, Pacbitun, and Xunantunich/San Lorenzo; Fig. 4.8). This relationship holds true if the single but extremely elevated $\delta^{34}S$ value from Calakmul is removed from the analysis ($U = 352.50$, $p = 0.000$). However, this is the opposite pattern than that observed among the faunal $\delta^{34}S$ values in Chapter 3, which may be related to the various subsistence catchments utilized by humans at each site. Indeed, the Nakum human $\delta^{34}S$ values are the least variable with a range of 0.8 ‰, suggesting these individuals obtained dietary sulfur from similar sources. The larger range of 1.6 ‰ from Mission San Bernabé and Xunantunich/San Lorenzo indicate slightly more variability in dietary protein at these sites

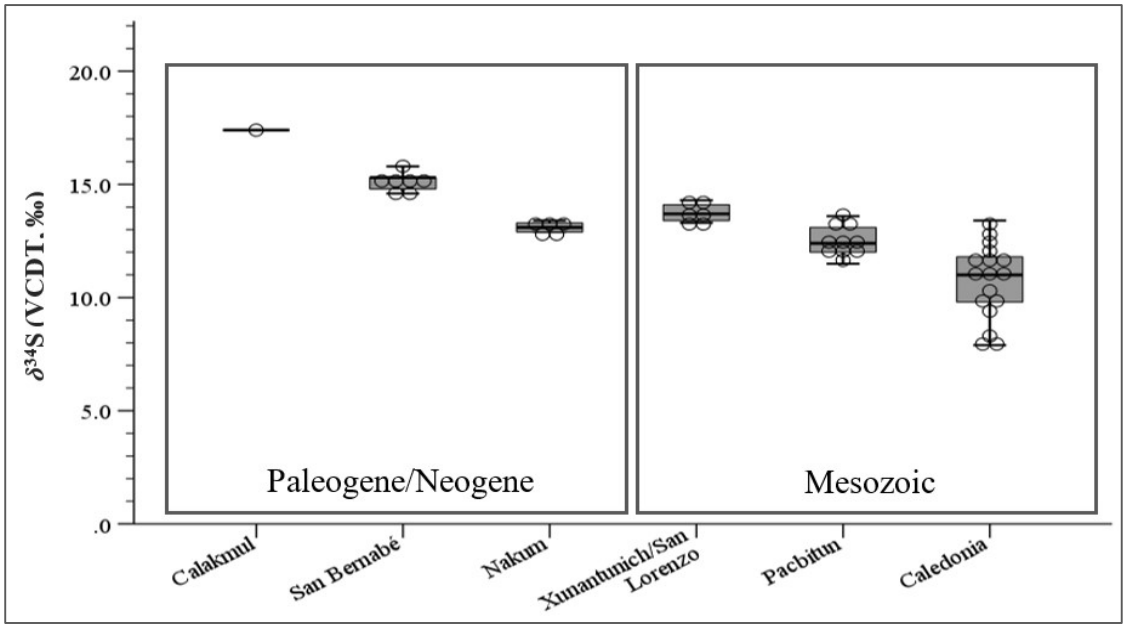

Figure 4.8: Boxplots of the δ^{34}S values by site after the outlying values from Xunantunich/San Lorenzo, Caledonia, and Pacbitun are removed arranged by underlying geology. Boxes represent the interquartile range (IQR), black bars represent the median, and whiskers represent the IQR*1.5 subtracted from the first quartile and added to the third. Transparent circles within the boxes and whiskers represent individual data points.

or perhaps variability in the underlying geology. The range of human δ^{34}S values from Pacbitun was higher at 2.8 ‰, although the greatest variability was evident in the values from Caledonia, which had a range of 6.4 ‰, indicating the individuals at this site had access to dietary protein sources with differing δ^{34}S values. Interestingly, the local Caledonia data set was the only one to exhibit a statistically significant positive relationship between the human δ^{34}S and δ^{13}C values ($r(17) = 0.755$, $p = 0.000$), suggesting that dietary carbon and sulfur came from the same source (Fig. 4.9). No other correlations between sulfur, carbon, or nitrogen isotope values were identified in any of the data sets.

As seen in Figure 4.10, the human δ^{34}S values are also generally lower than those of fauna from the three sites for which both were sampled, although this is variable (Table 4.8). At Nakum, the humans and terrestrial faunal had statistically similar δ^{34}S values ($U =$

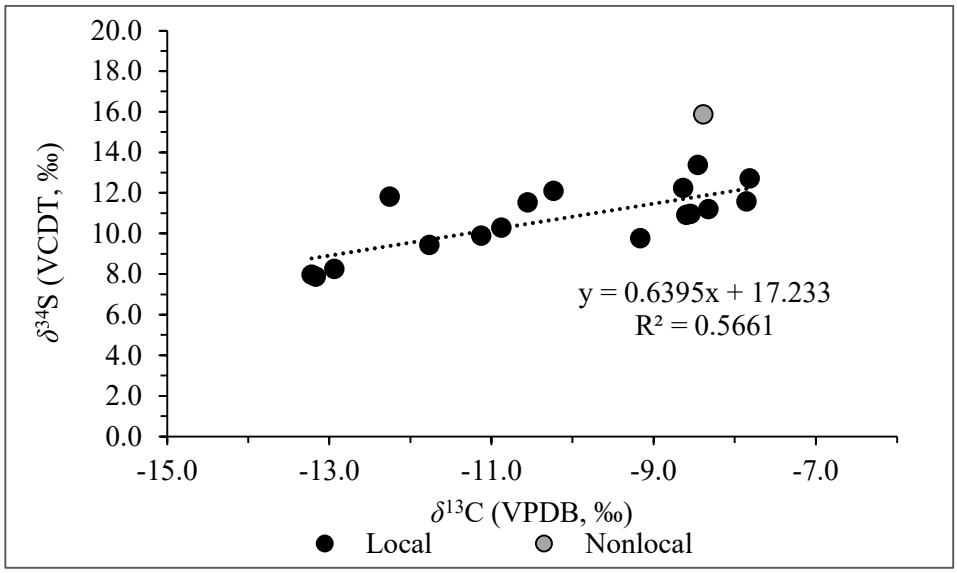

Figure 4.9: Significantly positive correlation (dotted line) between the $\delta^{34}S$ and $\delta^{13}C$ values from Caledonia (excluding the nonlocal individual).

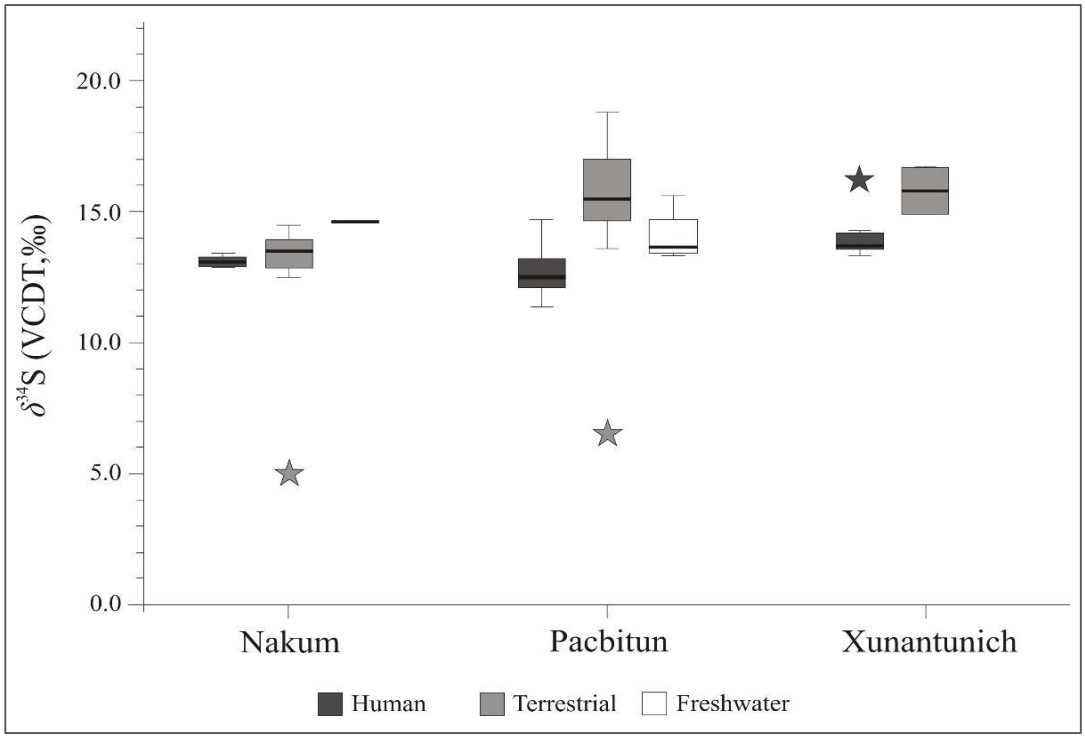

Figure 4.10: Boxplots of human, terrestrial fauna, and freshwater fauna $\delta^{34}S$ values from Nakum, Pacbitun, and Xunantunich. Boxes represent the interquartile range (IQR), black bars represent the median, and whiskers represent the IQR*1.5 subtracted from the first quartile and added to the third. Stars represent extreme outliers that fall beyond the IQR*3 subtracted from the first quartile and added to the third.

Table 4.8: Average and standard deviation of $\delta^{34}S$ values of human, terrestrial, and freshwater animals from Nakum, Xunantunich/San Lorenzo, and Pacbitun.

Site	Taxa	N	$\delta^{34}S$ (VCDT, ‰)	
			$\bar{x}$	σ
Nakum	Human	5	+13.1	0.2
	Terrestrial	14	+13.5	0.7
	Freshwater	1	+14.6	
Xunantunich/San Lorenzo	Human	6	+13.8	0.4
	Terrestrial	2	+15.8	1.2
Pacbitun	Human	10	+12.5	0.7
	Terrestrial	13	+15.6	1.3
	Freshwater	4	+14.0	1.1

Note: Individuals with outlying $\delta^{34}S$ values have been removed.

45.000, $p = 0.553$). In contrast, the average human $\delta^{34}S$ value is 2.0 ‰ lower than that of the fauna at Xunantunich, although this difference is also not statistically significant ($U = 12.00$, $p = 0.071$). There was, however, a statistically significant difference between the groups of taxa at Pacbitun ($F(2) = 21.439$, $p = 0.000$), whereby human $\delta^{34}S$ values were significantly lower than those of terrestrial fauna ($p = 0.000$), but not freshwater turtles ($p = 0.111$).

4.5 Discussion

Drawing on archaeological and historical evidence, in conjunction with the faunal $\delta^{34}S$ values discussed in Chapter 3 and previously published strontium ($^{87}Sr/^{86}Sr$) and stable oxygen ($\delta^{18}O$) isotope values for several of the individuals, the following discussion contextualizes the $\delta^{34}S$, $\delta^{13}C$, and $\delta^{15}N$ values presented above. The spatial distribution of human $\delta^{34}S$ values across the sites included in this study differ from those evidenced by the faunal baseline data presented in Chapter 3 (Rand et al. 2021a). The subsistence practices

at Maya sites revealed through the human isotopic data are thus explored to better understand the utilization of multiple catchments. Despite this variability, it is still possible to identify nonlocal individuals at Maya sites using stable sulphur isotope values and to reveal human migration later in life than previously possible using $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values from bone and dental enamel.

4.5.1 Spatial Distribution of Sulfur Isotope Values

As was the case with the faunal remains considered in Chapter 3 (Rand et al. 2021a), the range of $\delta^{34}S$ values of humans from inland sites (+7.9 to +16.2 ‰; Table 4.2) were higher than expected based on previous studies in other archaeological contexts (e.g., 2.3 to 14.2 ‰ at sites in the Danube Gorges; Nehlich et al. 2010). As all seven Maya sites are located considerably inland, it is unlikely the $\delta^{34}S$ values were influenced by the sea spray effect. Furthermore, although marine resources were traded to inland sites, it is unlikely they were consumed in sufficient quantities to influence isotopic values (Somerville et al. 2013:1548). Rather, these elevated $\delta^{34}S$ values are attributed to the underlying limestone geology, which formed through the evaporation of ancient seas (Day 2007) and thus has higher $\delta^{34}S$ values than other types of inland geology (Bottrell and Newton 2006; Claypool et al. 1980; Nielsen et al. 1991). However, unlike the faunal $\delta^{34}S$ values presented in Chapter 3 (Rand et al. 2021a), the human $\delta^{34}S$ values from sites located on Paleogene/Neogene limestones (Calakmul, Mission San Bernabé, and Nakum) were significantly higher than those located on Mesozoic limestones (Xunantunich/San Lorenzo, Pacbitun, and Caledonia). This may be explained by either methodological (i.e., differing analytical methods or sampling strategies) or Maya cultural factors.

First, it is possible that the human samples analyzed at one lab have higher $\delta^{34}S$ values than they would if analyzed at a different lab (Appendix B). This, however, seems unlikely, given that the $\delta^{34}S$ values from Nakum, a site located on Palaeogene/Neogene limestone, were statistically similar to those analyzed at the same laboratory from Pacbitun, located on Mesozoic limestone, and both were similar to samples analyzed by a different laboratory from Xunantunich and San Lorenzo, which is also located on Mesozoic limestone (Table 4.7).

A second explanation relates to sampling bias, wherein the sites from which the human samples originated were located on Paleogene/Neogene soils in Peten and southern Campeche, whereas the majority of faunal remains from sites on this lithology were situated in northern Belize near the Caribbean coast (Chapter 3). However, the proximity of the Belizean sites to the Caribbean coast would likely cause the faunal $\delta^{34}S$ values from the sites located on Paleogene/Neogene soils to be higher due to the sea spray effect (Gravenhorst 1978; Wakshal and Nielsen 1982), when in fact they are lower than those from Mesozoic sites.

The final explanation is that the terrestrial faunal remains accurately reflect environmental $\delta^{34}S$ values throughout the Maya region, and that the Maya values differ from the faunal baselines due to human subsistence practices, which were influenced by available foods and well as changing political, social, and cultural situations. In general, the human $\delta^{34}S$ values are also more homogenous than those of the fauna, indicating use of a broader dietary niche and possibly reliance on lime-processed maize grown in designated areas at each site. Because various Maya subsistence practices are the most likely explanation, these are explored in more detail below.

4.5.2 Isotopic Evidence for Maya Subsistence

The combination of stable sulfur, carbon, and nitrogen isotope analysis revealed that the Maya included in this study consumed a maize-based diet supplemented with other plants and animal protein that was largely derived from catchments near the sites at which they lived. The human $\delta^{13}C$ and $\delta^{15}N$ values in this study are consistent with those previously reported from Caledonia (Rand 2012; Rand et al. 2015b), Pacbitun (Coyston et al. 1999; White et al. 1993), Xunantunich and San Lorenzo (Freiwald 2011a, 2011b), and Calakmul (Price et al. 2018a). They are also in agreement with studies of Maya subsistence practices at other prehispanic sites, where elevated human $\delta^{13}C$ and $\delta^{15}N$ values relative to those of analyzed fauna have been interpreted as resulting from the consumption of a maize-based diet supplemented by C_3 plants and animal protein (Ebert et al. 2019; Gerry and Krueger 1997; Somerville et al. 2013; Tykot 2002; Whittington and Reed 1997a; Wright 2006). Because stable sulfur isotope values vary depending on the underlying geology as well as by ecosystem (i.e., terrestrial versus freshwater), the combined interpretation of $\delta^{34}S$, $\delta^{13}C$, and $\delta^{15}N$ values from humans and fauna reported in this study provide novel insights into Maya subsistence practices.

4.5.2.1 Prehispanic Maya Subsistence Practices

Although the terrestrial fauna species from three of the sites included here have elevated $\delta^{34}S$ values due to the underlying limestone, the consumption of freshwater animals and those imported from the Maya Mountains may contribute lower $\delta^{34}S$ values to Maya tissues (Chapter 3). The average human $\delta^{34}S$ values from Xunantunich/San Lorenzo, Nakum, and Pacbitun were consistently lower than those of the terrestrial fauna from these

sites, which may initially appear to be the result of the consumption of freshwater protein. However, the average human $\delta^{34}S$ values were also lower than the values of freshwater turtles at both Nakum and Pacbitun (Table 4.6).

Rather than the consumption of freshwater resources, the trophic level offset in $\delta^{34}S$ values caused by fractionation during the incorporation of dietary sulphur into consumer tissues ($\Delta^{34}S_{tissue\text{-}diet}$) may be larger than the typically cited +0.5 ± 2.4 ‰ (Nehlich 2015:6). This value was calculated by compiling data primarily from whole insects, as well as the muscle, hair, and cartilage of terrestrial mammals (see Nehlich 2015:6) and may not accurately reflect the offset associated with the incorporation of sulfur into the bone collagen of mammals such as humans. Indeed, a controlled feeding experiment has found that pig bone collagen $\delta^{34}S$ values are on average 1.5 ‰ lower than those of the diet (Webb et al. 2017). Because breastfeeding children are a trophic level above their mothers, their $\delta^{34}S$ values may be lower than that of adults from the same site. The $\delta^{15}N$ value (+11.6 ‰) of a 3- to 5-year-old from Burial 1 at Caledonia was elevated relative to the average of the adults ($\bar{x}$ = +8.3 ± 0.7 ‰, n = 5) from the same context, suggesting this subadult was breastfeeding (Fuller et al. 2006). Interestingly, the $\delta^{34}S$ value (+9.4 ‰) of this subadult was 1.6 ‰ lower than the average value of five adults ($\bar{x}$ = +11.0 ± 0.7 ‰) from the same context. At Roman period Oxfordshire, Nehlich et al. (2011) attributed lower $\delta^{34}S$ values of subadults aged 2 to 4 years to a weaning diet based on freshwater fish, although this could instead represent a larger trophic level shift in $\delta^{34}S$ values than previously thought.

However, the study by Webb et al. (2017) analyzed the $\delta^{34}S$ values of the whole diet consumed by the pigs, rather than methionine from the protein component that is routed to collagen, which may explain the larger offset they observed. More recently, the $\delta^{34}S$

values of the bone collagen of ancient foxes and their prey were found to be indistinguishable (Krajcarz et al. 2019), supporting the original interpretation that the trophic level offset minimally influences $\delta^{34}S$ values.

The $\Delta^{34}S_{tissue\text{-}diet}$ is an important area of future research, as it can alter the interpretations of sulphur isotopic results. For example, the Xunantunich/San Lorenzo individuals were likely reliant on both maize and terrestrial animal protein based on their elevated $\delta^{13}C$ and $\delta^{15}N$ values, respectively, and because their average $\delta^{34}S$ value ($\bar{x}$=+13.8±0.4‰) is more elevated than would be expected from the consumption of freshwater resources (see Chapter 3). However, the human $\delta^{34}S$ value is 2‰ lower than the average of two terrestrial faunal samples from Xunantunich. While this may be explained by the trophic level offset in $\delta^{34}S$ values, there are alternative explanations, including the consumption of freshwater resources as well as nixtamalized maize.

First, it is possible the Maya from these sites consumed freshwater resources or animals imported from the Maya Mountains in sufficient quantities to lower their $\delta^{34}S$ values relative to the locally available fauna. Alternatively, because riverine sulphate has been found to influence terrestrial $\delta^{34}S$ values (Nehlich et al. 2011), it is possible that lower $\delta^{34}S$ values were incorporated into maize cultivated on the floodplains of the Mopan River, or otherwise irrigated with river water, that was then consumed by the individuals from Xunantunich and San Lorenzo. Because nixtamalization doubles the amount of bioavailable methionine in maize (Katz et al. 1974), lower $\delta^{34}S$ values from river-irrigated maize may outweigh the sulfur derived from animal protein in Maya diets, which otherwise would contribute equal amounts of dietary methionine (Young and Pellett 1994). This example is, however, based on a comparison with two terrestrial animals who may not

accurately reflect the local variability of $\delta^{34}S$ values and could also benefit from the analysis of freshwater species from these sites. Regardless, a clearer understanding of $\Delta^{34}S_{tissue\text{-}diet}$ values could help differentiate among these possibilities.

The diet of the Nakum Maya is also difficult to interpret without a clearer understanding of variability in $\delta^{34}S$ values. The small sample of humans from Nakum (n = 5) had the most variable $\delta^{13}C$ and $\delta^{15}N$ values (Table 4.2), likely reflecting dietary differences over time and space, as well as among people of differing age, gender, and social status (Ebert et al. 2019; Freiwald 2011a; Gerry 1997; Gerry and Chesson 2000; White 2005). However, the human $\delta^{34}S$ values from Nakum were the least variable of all sites included in this study and were very similar to those of the terrestrial and freshwater fauna from this site. One explanation for this is that the trophic effect on $\delta^{34}S$ values is indeed negligible. Alternatively, it is possible that the humans were more reliant on freshwater resources with $\delta^{34}S$ values elevated relative to terrestrial fauna. The lower $\delta^{13}C$ values but elevated $\delta^{15}N$ and slightly elevated $\delta^{34}S$ values from Burials 4 and 7, for example, would be consistent with a diet based on freshwater protein if this were the case. However, this also seems unlikely, as the sulphur baseline for freshwater resources at Nakum is based on a single turtle (*Trachemys venusta*) sample with an unusually elevated $\delta^{34}S$ value (+14.6 ‰) relative to the average of the terrestrial animals from this site ($\bar{x}$ = +13.5 ± 0.7; Chapter 3; Rand et al. 2021a). Thus, the most plausible explanation for the elevated human $\delta^{34}S$ values is that the agricultural fields of the Nakum Maya were situated on nearby Quaternary limestone bedrock, which are expected to have much higher sulphur values than the Paleogene/Neogene limestones (Chapter 3; Rand et al. 2021a) on which most terrestrial fauna consumed by the Nakum Maya obtained their food. As at

Xunantunich and San Lorenzo, nixtamalization may also have increased the contribution of methionine from maize in the bone collagen of individuals from Nakum. Regardless, a clearer understanding of the degree to which $\delta^{34}S$ values fractionate when they are incorporated into the tissues of large mammals is necessary to clarify the relationship among the $\delta^{34}S$ values of faunal baselines and humans from the same site.

The combined data sets of $\delta^{34}S$, $\delta^{13}C$, and $\delta^{15}N$ values from human and fauna bone collagen also provide direct evidence of the utilization of catchments with divergent $\delta^{34}S$ values. For example, the lower average $\delta^{34}S$ values of the local Caledonia ($\bar{x}$ = +10.7 ± 1.6 ‰) and Pacbitun ($\bar{x}$ = +12.5 ± 0.7 ‰) individuals relative to the other Maya included in this study suggest their protein was acquired from the Maya Mountains or, at Caledonia, the Macal River. When the Pacbitun human $\delta^{34}S$ values are compared with the faunal baseline, it initially appears as though the Pacbitun Maya were more reliant on freshwater fauna than terrestrial animals, if $\Delta^{34}S_{tissue\text{-}diet}$ = –1.5 ‰ (Webb et al. 2017) is applied. It is, however, unlikely that freshwater resources made up a considerable component of the diet based on the elevated average human $\delta^{13}C$ values and because the $\delta^{15}N$ values are lower than expected for diets based on C_3-freshwater resources (Guiry 2019; Winemiller et al. 2011). A significant negative correlation between the $\delta^{15}N$ and $\delta^{34}S$ values is also expected if freshwater resources with lower $\delta^{34}S$ and higher $\delta^{15}N$ values compared to terrestrial animals were consumed in large quantities (Curto et al. 2019), but there is no such correlation in any of the Maya data sets analyzed here. It is also unlikely that the maize consumed by the Pacbitun and Caledonia individuals was irrigated with river water because Pacbitun is not situated on a large water course and the steep banks of the turbulent Macal River near Caledonia would have been difficult to farm compared to the calmer Mopan

River (Smith 1997). Both sites are also surrounded by agricultural terraces that undoubtedly provided the main subsistence base for these communities (Awe 1985:32; Healy et al. 1980, 2007).

Instead, it is possible that the lower human $\delta^{34}S$ values of the Caledonia and Pacbitun Maya are derived from protein acquired from the Maya Mountains. This is supported by the significantly positive relationship between the $\delta^{13}C$ and $\delta^{34}S$ values of the Caledonia Maya, demonstrating that C_3-based protein was acquired from the Maya Mountains whereas C_4-based protein was acquired from areas underlain by limestone, most likely the Vaca Plateau (Fig. 4.10). It is unlikely that maize was grown in the Mountain Pine Ridge region of the Maya Mountains, given its acidic soils derived from granite, shale, sandstone, quartzite, and some limestone (Wright et al. 1959). The region was, however,

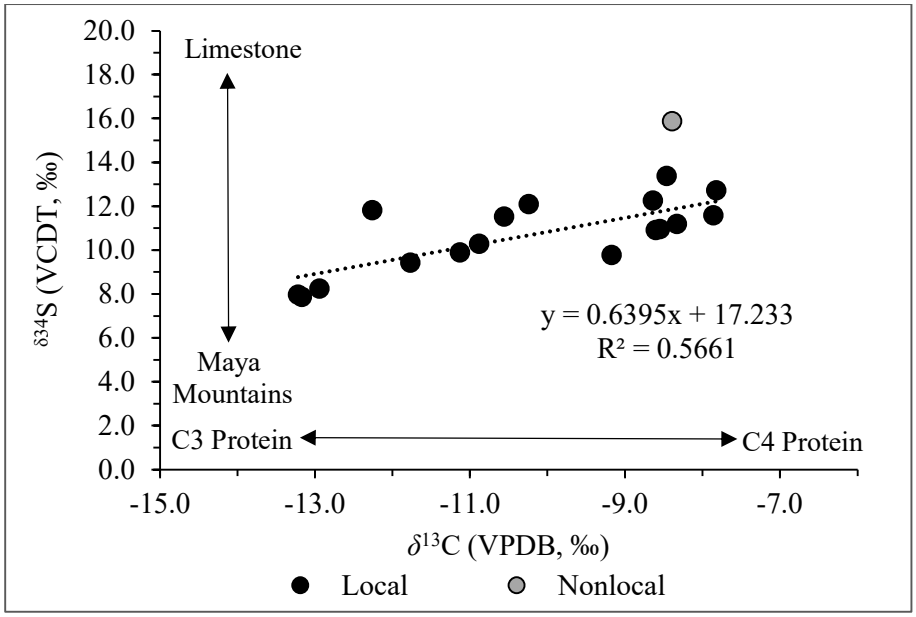

Figure 4.11: Statistically significant positive correlation (dotted line) between the $\delta^{34}S$ and $\delta^{13}C$ values from Caledonia (excluding the nonlocal individual). Elevated values indicate consumption of maize-based protein from limestone areas whereas lower values indicate the consumption of terrestrial animals from the Maya Mountains.

an excellent source of granite for manufacturing manos and metates, pine for torches and pine resin for pitch and incense, as well as mammals, namely deer (Awe 1985:32). Indeed, most nonlocal fauna in this study, including a deer from Pacbitun with a low $\delta^{34}S$ value, (+6.5‰; Appendix D) were likely obtained from the Maya Mountains (Chapter 3; Rand et al. 2021a). However, the large degree of variability in $\delta^{34}S$ values at Caledonia may reflect not only the use of multiple catchments, but also the relatively large sample size from this site. It is possible that the analysis of additional samples at other sites may also result in a greater range of $\delta^{34}S$ values and is an important avenue of future research. Regardless, the isotopic evidence presented here indicates that although the Maya at Caledonia and Pacbitun obtained most of their subsistence resources from the limestone environments surrounding their sites, they also obtained subsistence resources from the Maya Mountains. Access to multiple ecozones may also have been the reason why these sites were initially settled (Awe 1985; Healy 1990), an advantage the Maya continued to utilize throughout the occupation of these sites.

4.5.2.2 Colonial Period Maya Subsistence Practices

The individuals from Colonial period Mission San Bernabé had much more restricted diets than the prehispanic Maya included in this study, evidenced by their elevated and homogenous $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values. Colonial records state that the Spaniards restricted Maya diets, encouraging the rearing of cattle and cultivation of maize and beans and discouraging the use of more varied resources from the forest and home gardens (Schwartz 1990:54, 62). Although freshwater resources such as snails and turtles continued to be important in Colonial period Maya diets (Freiwald 2012; Freiwald and

Pugh 2018), the low δ^{13}C and high δ^{15}N values expected from freshwater resources were probably overridden by the consumption of maize-fed beef or dairy products with high δ^{13}C values and beans with low δ^{15}N values. Furthermore, reliance on freshwater fish is expected to be evidenced by lower δ^{34}S values, but the Mission San Bernabé individuals have the most elevated δ^{34}S values in this study other than the single individual from Calakmul. This suggests that although they may have consumed freshwater resources, but not in large quantities, and reliance on resources grown or reared on limestone with elevated δ^{34}S values was more important in the San Bernabé diet. The elevated δ^{13}C and δ^{15}N values indicate that dietary protein was not only acquired from the consumption of maize, but also likely European domesticates such as cows (*Bos taurus*) and pigs (*Sus scrofa*) foddered on maize.

To better understand the influence of Colonialism on Maya consumption patterns, the δ^{13}C and δ^{15}N values of the Colonial period (1697 – 1821 CE; Table 1.1) individuals from Mission San Bernabé were compared with those of individuals from the Contact period (1525 – 1697 CE; Table 1.1) at Tipu (Harvey 2018) and Lamanai (White et al. 1994) in Belize, and Campeche (Price et al. 2012) in Mexico. The δ^{13}C and δ^{15}N values of the San Bernabé individuals are elevated and more homogenous than the Contact period individuals (Table 4.9). While the variability in the isotopic values observed at Tipu may be the result of the larger sample size, similar variability is seen in the smaller samples of

Table 4.9: Bone collagen δ^{13}C and δ^{15}N values from Contact and Colonial period Maya sites.

Site	Time Period	$\delta^{13}C_{col}$ (‰, VPDB)			$\delta^{15}N$ (‰, AIR)			Source
		N	Mean	SD	N	Mean	SD	
San Bernabé	Colonial	7	–8.0	0.5	7	+10.0	0.3	This study
Tipu	Contact	42	–9.8	1.2	11	+9.2	0.7	Harvey (2018)
Lamanai	Contact	11	–9.9	0.9	9	+9.7	0.6	White et al. (1994)
Campeche	Contact	3	–9.7	1.9	3	+9.5	0.5	Price et al. (2012)

individuals from Lamanai and Campeche (Table 4.9), although the variability in the Campeche sample may be due to the presence of nonlocal individuals from Europe or Africa (Price et al. 2012). Regardless, it appears that the Colonial period Maya at Tipu and Lamanai enjoyed a more varied diet and consumption patterns at these sites were not influenced by the presence of the Spaniards (Harvey 2018:285; White et al. 1994:141). This is likely because the individuals from Tipu, Lamanai, and Campeche predate those from Mission San Bernabé, and thus the more restricted diets of the San Bernabé individuals may reflect increased Spanish control over Maya populations, including their subsistence patterns in later periods. It is thus evident from the isotopic evidence presented here that the arrival of the Spaniards was associated with a drastic dietary shift in Peten relative to prehispanic Maya subsistence practices and those at earlier Contact period sites in Belize and Mexico, which restricted access to traditional sources of protein while introducing new ones. The analysis of additional individuals from sites that date to the Contact and Colonial periods will further elucidate the impact of Spanish influence on Maya subsistence patterns.

4.5.3 Nonlocal Individuals at Maya Sites

In addition to subsistence practices, it is also possible to identify nonlocal individuals as those with $\delta^{34}S$ values that differ from individuals who consumed local sources of protein. While faunal baselines are useful for approximating local $\delta^{34}S$ values (Chapter 3), the unknown offset between diet and consumer tissues combined with human utilization of multiple dietary catchments precludes the identification of nonlocal humans using local faunal $\delta^{34}S$ values at this time. Rather, nonlocal humans were identified as having $\delta^{34}S$ values that were statistically different from those of other humans from the

same site. As a result, it is not possible to comment on the origin of the individual from Calakmul, as this site is represented by a single sample. However, three individuals, one each from Xunantunich, Pacbitun, and Caledonia, were identified as nonlocal individuals with $\delta^{34}S$ values that fell beyond two standard deviations of the mean of their respective sites (Table 4.5).

As discussed in Chapter 2, the isotopic analysis of multiple individuals in conjunction with other lines of evidence can elucidate the structure of past migrations (Fig. 2.1). Investigations of the temporality, spatial extent, social composition, and scale of migration require the analysis of large numbers of nonlocal individuals, which were not identified in this study. The analysis of multiple isotopes of tissues from the same individual that form at different ages can, however, indicate potential places of origin and the length of time an individual resided in an area prior to death. Despite equifinality, the multi-isotopic approach allowed potential places of origin from which several of the nonlocal individuals identified in this study originated to be inferred. Furthermore, a consideration of the burial contexts of individuals with both local and nonlocal individuals that relocated at different periods during life indicates the length of time they resided at their places of burial before death. Combined, these data are interpreted below and provide additional insight into prehispanic Maya conceptualizations of identity and broader sociopolitical aspects of the deposition of the dead as well as the impact of contact with Europeans on Maya migration patterns.

4.5.3.1 Local Individuals in Formal Funerary Contexts at Prehispanic Maya Sites

As mentioned in Chapter 2, the Maya did not use cemeteries to inter their dead, and

instead select individuals were interred within site architecture. Such contexts include formal burials of revered ancestors, dedicatory and termination deposits, and nonfunerary deposits that include human remains (Tiesler 2007; Welsh 1988). The inclusion of local individuals in formal funerary contexts within both ceremonial and residential complexes in particular may reflect not only ancestor veneration but also attempts by local lineages to solidify their legitimacy in the face of foreign influences (McAnany 1995).

At Xunantunich, for example, two burials from elite residential Group D, one of an older adult male buried in a chultun during the Late Preclassic period (Op. 21C Individual 1) and another adult buried in front of Str. D6 during the Late Classic period (Op. 74R) had local enamel $^{87}Sr/^{86}Sr$ (0.70903 and 0.70865, respectively) and $\delta^{18}O$ values (–1.4 ‰ and –2.8 ‰, respectively; Freiwald 2011a; Freiwald et al. 2014), as well as sulfur isotope values (+14.3 ‰ and +13.3 ‰, respectively). Similarly, all individuals with local $\delta^{34}S$ values from the Pacbitun Epicentre regardless of time period were interred in the Eastern Triadic Assemblage, reflecting their status as ancestors (Awe et al. 2016). This pattern may have been emulated by lower status individuals in the core zone of Pacbitun during the Terminal Classic, who also buried individuals with local $\delta^{34}S$ values in eastern structures at this time. Furthermore, all individuals from formal funerary contexts at Nakum had local $\delta^{34}S$ values, despite their varied contexts, biological profiles, and chronologies.

All of the local individuals from Caledonia were also interred in formal funerary contexts, including those from multiple burials. While the presence of multiple individuals in the same burial was initially interpreted as representing individuals sacrificed for inclusion with a primary individual, revaluation of these contexts indicates multiple individuals could also represent secondary funeral rites, ongoing tomb use, and skeletal

curation and reuse of bones (Weiss-Krejci 2003). Indeed, both Burial 1 and Burial 4 at Caledonia contained the remains of multiple individuals and are interpreted as sequentially used family tombs (Healy et al. 1998; Rand 2012; Rand et al. 2015b), whereas Burial 3 may represent an intrusive sacrificial burial, although perimortem trauma was not identified on any of the four individuals from this burial (Awe 1985:110-111; Rand et al. 2015b). Regardless, all individuals excluding one from Burial 4, discussed in more detail below, had local δ^{34}S values and their δ^{18}O values indicate origins near the site (Rand 2017). The continued use of tombs by individuals from local lineages illustrates their ties to the community and the centre of Caledonia.

It should be noted that most of these individuals were identified as local based on δ^{34}S values from their bone collagen, and it is not possible to determine if they lived elsewhere as children or if they resided in a different region with similar environmental sulfur isotope values prior to burial. Regardless, it appears that the individuals interred in formal funerary contexts lived near the sites where they were buried for many years prior to death, and the social practice of local ancestor veneration that began in the Late Preclassic period lasted throughout the subsequent Classic period.

4.5.3.2 Nonlocal Individuals in Non-Funerary Deposits at Prehispanic Maya Sites

At Maya archaeological sites, human remains may also be recovered from contexts that lack a clear funerary status (i.e., non-funerary deposits; Tiesler 2007). For example, "problematic deposits" (PDs) may or may not contain human remains, but those that do are classified as neither a cache nor burial, as the behaviours that led to their formation are often difficult to discern (Aimers et al. 2020; Moholy-Nagy 2020; Tiesler 2007). Tiesler

(2007) further differentiates PDs (containing scattered human remains) from primary disposals (disturbed or undisturbed skeletons that lack evidence for ancestral treatment, often uncritically identified as sacrificial victims), although the PD subcategories of termination and dedicatory deposits recently reassessed in the literature (e.g., Aimers et al. 2020; Moholy-Nagy 2020; Newman 2019) will be explored here.

Human remains from PDs at Maya sites are not typically subjected to isotopic analyses, as such contexts are difficult to interpret, and researchers tend to focus on the analysis of remains from formal funerary contexts (but see Freiwald et al. 2014; Rand et al. 2020a). However, as discussed below, the nonlocal origins of all three individuals sampled from termination and dedicatory deposits in this study demonstrates how isotopic analysis can contribute to the interpretation of the behaviours that led to the formation of such deposits.

Termination deposits refer to numerous assemblages and depositional behaviours generally associated with ritual deactivation of structures or sites (Aimers et al. 2020; Newman 2019). Such contexts typically show evidence of the destruction of material culture (e.g., ceramics, architecture, etc.), and human remains may be found in these deposits as both scatters of bone, perhaps indicative of ancestor bundles, as well as complete and articulated human burials (Aimers et al. 2020:71-72). While termination deposits are variable and their interpretation in Maya archaeology has recently been reassessed (Newman 2019), researchers generally further subdivide termination deposits to those that are reverential and those that are desecratory (Aimers et al. 2020; Newman 2019; Pagliaro et al. 2003; Tsukamoto 2017). Reverential termination deposits are viewed as intermediate between dedication and termination deposits and involve ancestor veneration,

including the "movement of human bones from their primary interment into a secondary location [and] inclusion of human bone within ritual contexts" (Aimers et al. 2020:72). The two individuals recovered from termination deposits included in this study instead come from desecratory termination deposits that are typically associated with the decommission of buildings and spaces and "may involve the purposeful disturbance and/or desecration of elite burials as well as the remains of ritually sacrificed elite inhabitants of a Maya community" (Pagliaro et al. 2003:80).

The young adult male from a Late Classic II or Terminal Classic termination deposit in Str. A11 at Xunantunich (Op. 302G) falls into the desecratory termination deposit category or Tiesler's (2007) primary disposal category. The context, osteological profile, and position of the body associates the deposition of the individual with destruction of parts of the structure, ritual activity, and violence (Freiwald et al. 2014; Yaeger 2005; see also Berryman 2007:394), although no perimortem trauma was noted on the skeleton. Importantly, his nonlocal enamel $^{87}Sr/^{86}Sr$ (0.70797) and $\delta^{18}O$ (–0.32 ‰) values are typical of the central Peten, indicating he originated elsewhere (Freiwald 2011a). However, because enamel forms during childhood, it was difficult to discern whether he was a recent arrival, which would support the possibility that he was a captive, or if he had resided at Xunantunich for some time prior to death (Freiwald 2011a:144). His elevated, nonlocal $\delta^{34}S$ value (+16.2 ‰) is also consistent with those from Peten and reveals that he was indeed a recent arrival to Xunantunich.

While it is not possible to unequivocally state this young man was captured and brought to his final resting place as a sacrificial victim, his inclusion in a termination deposit during a dramatic political change at Xunantunich may represent a severing of ties with his

place of origin (Freiwald et al. 2014) and/or the demonstration and legitimization of elite power through the sacrifice of their rivals (Demarest 1984; Inomata and Triadan 2003:204). Thus, this desecratory termination deposit represents the political motivations behind those who included him in the deposit at a time of uncertainty at Xunantunich.

Similarly, an adult interred as part of a termination deposit at the summit of Str. 99 (III-1-2) at Nakum during the Terminal Classic period (Źrałka et al. 2014) falls into the desecratory category. However, unlike the Xunantunich individual, the bones of the Nakum individual were not articulated and therefore would constitute Tiesler's (2007) isolated bone scatter category. This individual had a nonlocal bone apatite $\delta^{18}O$ value (–8.7 ‰), suggesting he/she was a recent arrival from central or southwestern Mexico, the Guatemalan Highlands, or along the Pacific Coast (Chapter 5; Rand et al. 2020a). Although his or her $\delta^{34}S$ value (+13.3 ‰) fell within the local range, similar values may also be found in central and southwestern Mexico and perhaps along the Pacific coast (Chapter 3; Rand and Grimes 2017; Rand et al. 2021a). The multi-isotopic approach applied here helped circumvent the equifinality of $\delta^{34}S$ values in various parts of the Maya region and successfully identified this individual as nonlocal. As with the termination deposit at Xunantunich (Freiwald et al. 2014), it is not possible to determine if this individual was a war captive or if he/she was sacrificed, but the inclusion of a nonlocal individual in the termination deposit on Str. 99 at Nakum may reflect the severing of ties with that person's place of origin during a time of political turmoil (Chapter 3; Rand et al. 2020a).

It is also possible that an individual's nonlocal origin was important for his or her inclusion in other non-funerary deposits. Dedication deposits, for example, are related to the ritual consecration of structures and spaces to ensoul built places and are often

associated with renovation or rededication but not destructive behaviour (Aimers et al. 2020:71; Pagliaro et al. 2003:76). For example, an adult of indeterminate sex interred in Burial 2, a dedicatory context beneath Stela 2 at the base of Str. 5 (BU 5-2) at Pacbitun during the Terminal Classic was interpreted as sacrificial (Healy et al. 2004b:215; Robertson 2011). As with the termination deposits from Xunantunich and Nakum, this dedicatory burial had a nonlocal δ^{34}S value (+14.7 ‰) and was interred during a period of sociopolitical change at Pacbitun just prior to the abandonment of the site. Unfortunately, the reason for the placement of Stela 2 in front of the E Group during the Terminal Classic is unknown because it was not carved and therefore the "sub-stela interment may have been placed as a dedication to honor the ancestors, a cycle of time, architectural renewal, or even to commemorate the erection of the stelae itself" (Micheletti 2016:78).

Burial activity associated with dedicatory deposits may also serve to reinforce ancestral ties to land or legitimate power (McAnany 1995). The nonlocal origin of the Pacbitun individual within a dedication deposit may therefore represent a strengthening of foreign ties during a turbulent period in the site history, in contrast to the severing of foreign ties possibly represented by the inclusion of nonlocal individuals in desecratory termination deposits (Freiwald et al. 2014; Rand et al. 2020a; see also Chapter 5). A study of oxygen isotope values, however, found both local and nonlocal individuals among dedicatory burials at Altun Ha, although the inclusion of nonlocal individuals appears to have increased from the Preclassic to Terminal Classic periods (Olsen et al. 2014). This suggests that the relationship between origin and inclusion in dedicatory deposits is complicated and the importance of including nonlocal individuals in these contexts varied over time.

Overall, an individual's nonlocal origin appears to correlate with nonfunerary contexts and may symbolize the strengthening or severing of ties with their place of origin. While isotopic studies do not typically focus on individuals from nonfunerary contexts, the results presented here demonstrate that the analysis of such individuals can provide more detailed interpretations of the behaviours that contributed to the formation of nonfunerary and "problematic" deposits containing human remains.

4.5.3.3 Nonlocal Individuals in Funerary Contexts at Prehispanic Maya Sites

Although the majority of nonlocal individuals identified in this study came from non-funerary contexts, the degree to which nonlocal individuals were incorporated into receiving communities may also be elucidated from their burial in formal funerary contexts within ceremonial architecture at Maya sites. For example, an adult of indeterminate sex interred in Burial 4 at Caledonia (C2-4 F6) during the Late Classic period. This individual's δ^{34}S value (+15.9 ‰) exceeded the broad local range for Caledonia and suggests an origin in Peten or possibly a coastal region. Although this individual's bone apatite δ^{18}O (–4.3 ‰; Rand 2017) appears too low for him/her to have originated to the west, when it is adjusted by +1.7 ‰ to make it comparable to the δ^{18}O values of tooth enamel (Warinner and Tuross 2009), it falls within the range of values reported in Peten (Price et al. 2008, 2010; Wright 2012; Wright et al. 2000). Caledonia Burial 4 was initially interpreted as a tomb containing two primary burials and two sacrificial burials (Awe 1985:115), although as mentioned above, reanalysis of the skeletal remains and archaeological context indicate it was a sequentially used tomb that contained the remains of at least seven individuals (Rand 2012; Rand et al. 2015b). It is similar to Burial 1 at Caledonia (Healy et al. 1998), and if it is also

a family tomb, then the inclusion of a nonlocal individual may reflect a nonlocal person who was integrated into the Caledonia community.

Similarly, a middle-aged female interred in SL -13 Str. 6 at San Lorenzo during the Late Classic I period (Op. 243 LL/3) likely grew up near the Macal River based on her enamel $^{87}Sr/^{86}Sr$ value (0.70938; Freiwald 2011a:149-152). The problem of equifinality precludes identifying whether she was a recent migrant, as her sulfur value (+13.4 ‰) falls within the local ranges of both Xunantunich/San Lorenzo as well as Caledonia, the latter of which is situated on the Macal River. However, her burial in the only ceremonial structure at the site (Yaeger 2000) may indicate that despite having resided elsewhere as a child, she had become fully integrated into the local community regardless of the length of time she resided at San Lorenzo prior to death.

While nonlocal individuals may have been preferentially included in nonfunerary context, a nonlocal origin did not necessary preclude individuals from being integrated into receiving communities, as in our own. These results confirm that identity construction among the Maya was complex and future multi-isotopic analysis of individuals from both funerary and nonfunerary contexts at Maya sites will provide greater insights into Maya perspectives of identity and the sociopolitical factors that caused some individuals to be included in specific contexts.

4.5.3.4 Colonial Impacts on Maya Migration

Finally, the Colonial period individuals from Mission San Bernabé appear to have lived either at the site or in a nearby area with similarly elevated $\delta^{34}S$ values for several years prior to being buried in the church. Missions established along the banks of the Peten

lakes during the early Colonial period involved both the concentration of small but dispersed local groups as well as the relocation of entire settlements from farther away (Gasco 2005). For example, following British incursions along the Belize River Valley, the Spaniards moved the Maya from Tipu in Belize to the shores of Lake Peten Itza in 1707 CE (Graham et al. 1985:207-210). Mission San Bernabé was established prior to 1712 CE, several years after the other missions in the region (Jones 1998:Table 15.4).

Given the local $\delta^{34}S$ values from the Mission San Bernabé individuals presented here, combined with the local $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values of most of the individuals analyzed by Freiwald and colleagues (2020), it is likely the mission comprised the concentration of local individuals, rather than the relocation of those from distinct isotopic regions. The burials included here also span the occupation history of the site and it is possible that many residents were descended from migrants to the region.

Interestingly, the enamel of the second maxillary molar from a young adult male from Burial 18, one of the first to be interred in the church based on its western location (Pugh et al. 2016), had a $\delta^{18}O$ value (+2.8 ‰) that fell within the local range, but a nonlocal $^{87}Sr/^{86}Sr$ value (0.708489), indicating he spent his childhood from 2.5 to 8 years of age (AlQahtani et al. 2010) to the east (Freiwald et al. 2020). However, the $\delta^{34}S$ (+14.6 ‰) of his right clavicle fall within the local range presented in Table 4.6, and the $\delta^{18}O$ (–3.8 ‰) of his bone apatite also falls within the range (Freiwald et al. 2020: Table 1), even when adjusted for comparison with enamel (–2.1 ‰; Warinner and Tuross 2009), indicating he lived at the site for many years prior to his death. The potential early date of his burial combined with the isotopic data suggest this young man may have relocated from an area to the east, possibly from Tipu in 1707 CE or perhaps earlier as part of ongoing population

exchange that predated the arrival of the Spanish and establishment of missions in the region (Freiwald et al. 2020). Regardless, the isotopic data demonstrate that he lived elsewhere as a child and had resided in the area surrounding Lake Peten Itza many years prior to his death.

While isotopic evidence suggests a high degree of mobility at Colonial period Tipu due to Maya resistance to Spanish colonialism (Trask 2018), there is considerably less isotopic and archaeological evidence for migration to Mission San Bernabé (Freiwald et al. 2020). This may be because the extensive population movement that frustrated Spanish officials (Farriss 1984; Restall 1997) occurred over short distances or within isotopically similar regions, or that Maya resistance to Spanish colonialism via migration lessened over time. It is nevertheless apparent that the arrival of Europeans significantly altered the nature of migration throughout the Maya region (Trask 2018) and the analysis of additional individuals from Contact and Colonial period sites will further contribute to understandings of how the arrival of Europeans disrupted Maya migration patterns.

4.6 Chapter 4 Summary and Conclusions

The stable sulfur isotope analysis of 49 humans from seven Maya sites has contributed to new understandings of Maya subsistence strategies and migration. The spatial distribution of $\delta^{34}S$ values in human and terrestrial faunal values differed, most likely reflecting social, political, and economic factors that influenced Maya use of isotopically distinct subsistence catchments near different sites and possibly Maya consumption of lime-processed maize. Although the offset in $\delta^{34}S$ values of consumer tissues and their diets are not well defined, consideration of the $\delta^{13}C$ and $\delta^{15}N$ values

revealed that lower human $\delta^{34}S$ values are unlikely to be from the consumption of substantial amounts of freshwater protein. Instead, subsistence strategies, such as the cultivation of maize crops on floodplains at Xunantunich and the consumption of terrestrial fauna from the Maya Mountains at Caledonia and Pacbitun may explain the lower human $\delta^{34}S$ values from these sites. The isotopically homogenous diet of the Colonial period individuals from Mission San Bernabé also show that the arrival of Europeans disrupted Maya subsistence patterns established during earlier periods.

Despite the variability caused by Maya utilization of multiple resource catchments that complicates interpretations of subsistence, the identification of three nonlocal individuals with outlying $\delta^{34}S$ values indicates this technique is useful for studies of migration in the past. While small sample sizes precluded a detailed assessment of the structure of Maya migration proposed in Chapter 2, the comparison of the $\delta^{34}S$ values with previously published strontium and oxygen values from the same individuals that reflect childhood migration reveals the length of time people lived in their place of burial prior to death. For example, a young man from Colonial period Mission San Bernabé (Burial 18) appears to have spent his childhood in an isotopically distinct region but had lived near Lake Peten Itza long enough to have developed local bone $\delta^{34}S$ values. Because his burial is one of the oldest in the mission church, it is possible that he represents a migrant from the east who possibly relocated as a result of the resettlement of Maya populations in the Peten Lakes region by the Spaniards during the early Colonial period.

These data may also reveal the degree to which nonlocal individuals were integrated into prehispanic Maya communities. For example, a young male who was included in a desecratory termination deposit (Op. 302G) was a recent migrant to Xunantunich, and his

nonlocal origin may have signified the severing of ties between this site and his place of origin. Although equifinality indicated another individual from a desecratory termination deposit at Nakum had a local $\delta^{34}S$ value, his/her nonlocal bone $\delta^{18}O$ value indicates he/she was indeed a recent migrant to the site. Conversely, a recent migrant to Pacbitun (BU 5-2) suggests that origin may also have been important in dedicatory contexts, representing the strengthening of ties between regions. Nonlocal individuals were not, however, solely interred in non-funerary deposits, and the inclusion of an individual born elsewhere in formal funerary contexts, such as a sequentially used family tomb along with local ancestors at Caledonia and in the only ceremonial context at San Lorenzo speaks to the integration of these individual into receiving communities. It is also important to consider the impact that contact with Europeans had on disrupting long-established migration patterns in the Maya lowlands.

The results presented herein highlight a number of factors that influence the $\delta^{34}S$ values of Maya collagen and must be considered when interpreting these data in future studies. As previously demonstrated in Chapter 3, bioavailable $\delta^{34}S$ values vary depending on the type and age of the underlying geology and distance from the coast, although equifinality currently prevents identification of specific places of origin. The analysis of additional human and faunal bone collagen samples from areas underrepresented in this study, including the Northern Lowlands, central Peten, Highlands, and western Honduras, will undoubtedly reveal the degree of spatial variability in $\delta^{34}S$ values across the Maya region, further contributing to the identification of nonlocal individuals who recently migrated from isotopically distinct areas.

However, the geospatial distribution of $\delta^{34}S$ values is not the only factor to consider when interpreting the values of human bone collagen. For example, the diets of organisms affect the $\delta^{34}S$ of their consumers, as seen in the marine-influenced limpkin diets at Vista Alegre presented in Chapter 3 and Maya consumption of freshwater animals discussed in this chapter. The consumption of fauna from multiple isotopically distinct catchments at Caledonia and the possible location of agricultural fields in alluvial soils near the Xunantunich polity also demonstrate how social and economic factors can influence $\delta^{34}S$ values of Maya bone collagen away from underlying baseline assumptions derived from environmental parameters. Better characterization of methionine routing from different dietary components (i.e., protein from animal tissues versus lime-processed maize) and trophic level offsets (i.e., $\Delta^{34}S_{tissue\text{-}diet}$) between the diets of large mammals and their bone collagen could also help to further differentiate the type of dietary protein consumed by the Maya. Thus, researchers should identify potential dietary sources of isotopic variation in addition to geospatial factors when interpreting the $\delta^{34}S$ values of human bone collagen.

Nevertheless, this study demonstrates how the integration of stable sulfur and other isotope analyses in a multi-isotopic, multi-tissue, biocultural approach complements and expands upon current understandings of Maya subsistence practices and migration. The case study presented in the following chapter illustrates the potential of using such an approach in conjunction with archaeological data to reconstruct dietary practices and identify nonlocal individuals at Nakum, Guatemala.

CHAPTER 5

PREHISPANIC MAYA DIET AND MOBILITY AT NAKUM, GUATEMALA: A MULTI-ISOTOPIC APPROACH[10]

Human subsistence strategies and mobility are socially mediated practices, and their study provides insights into myriad sociocultural aspects of past societies (Anthony 1990; Cucina 2015a; Gumerman 1997; Hastorf 2017; van der Veen 2003). Isotopic techniques are advantageous in archaeological studies because they provide direct evidence for mobility and diet at the individual level. Stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope analyses are well-established methods for investigating diet among the prehispanic Maya (see Somerville et al. 2013; Tykot 2002), as are strontium ($^{87}Sr/^{86}Sr$) and stable oxygen ($\delta^{18}O$) isotope techniques for identifying nonlocal individuals at Maya sites (Price et al. 2008; Scherer et al. 2015; Wright 2012). Stable sulfur ($\delta^{34}S$) isotope analysis is a relatively novel technique for investigating both diet and mobility in the past (Craig et al. 2010;

[10] A version of this chapter was co-authored with Varinia Matute as well as Drs. Vaughan Grimes, Carolyn Freiwald, Jarosław Źrałka, and Wiesław Koszkul and published in the *Journal of Archaeological Science: Reports* (Rand et al. 2020a). JZ and WK provided samples for analysis, VM conducted osteological analyses, VG and CF provided resources and supervision, and all co-authors provided comments on initial drafts of this chapter. The Nakum isotope data is also presented in a chapter in a monograph of the site that is currently under review (Rand and Freiwald under review). The dissertation author is the primary author of both publications and was responsible for the research design, preparing and weighing the samples for isotopic analysis, analysing and interpreting the results, writing the original manuscripts, editing various drafts, and submitting the manuscripts for publication.

Drucker et al. 2018b; Nehlich 2015; Nehlich et al. 2010; Privat et al. 2007; Rand and Nehlich 2018; Richards et al. 2001) and offers a promising corroborative technique in the Maya region (Awe et al. 2017; Green 2016; Rand and Grimes 2017).

Nakum is a prehispanic Maya centre in the Peten region of northeastern Guatemala that was occupied from the Middle Preclassic period (c. 800–300 BCE), through the Protoclassic (100/50 BC-AD 250/300), Early Classic (AD 300–600), and Late Classic (AD 600–800) periods before it was abandoned during the Terminal Classic (AD 800–950) period (Koszkul et al. 2006, 2009; Źrałka and Hermes 2012; Źrałka and Koszkul 2007; Źrałka et al. 2014, 2017, 2018). However, little is known of the diets or mobility histories of the prehispanic Maya who lived at the site, which can provide broader insights into subsistence practices and interregional interaction. This study demonstrates how the combination of isotopic assays – a multi-isotope approach – identified the long-distance migration of humans to Nakum from multiple locations while characterizing the use of local and regional catchments as well as imported animal resources.

5.1 Archaeological and Environmental Context

Nakum is situated on the banks of the Holmul River, 25 km east of Tikal and 11 km north of Lake Yaxha in the Peten region of Guatemala (Fig. 5.1). Peten has a humid tropical climate and experiences a dry season from December to May, followed by a wet season from June to November punctuated by a midsummer drought (Magaña et al. 1999). The average temperature is 25 °C and the average annual precipitation varies from 900 to 2500 mm with a regional mean of 1601 mm (Deevey et al. 1980). Nakum is underlain by Paleocene limestone bedrock and is generally level with an average elevation of 200 m

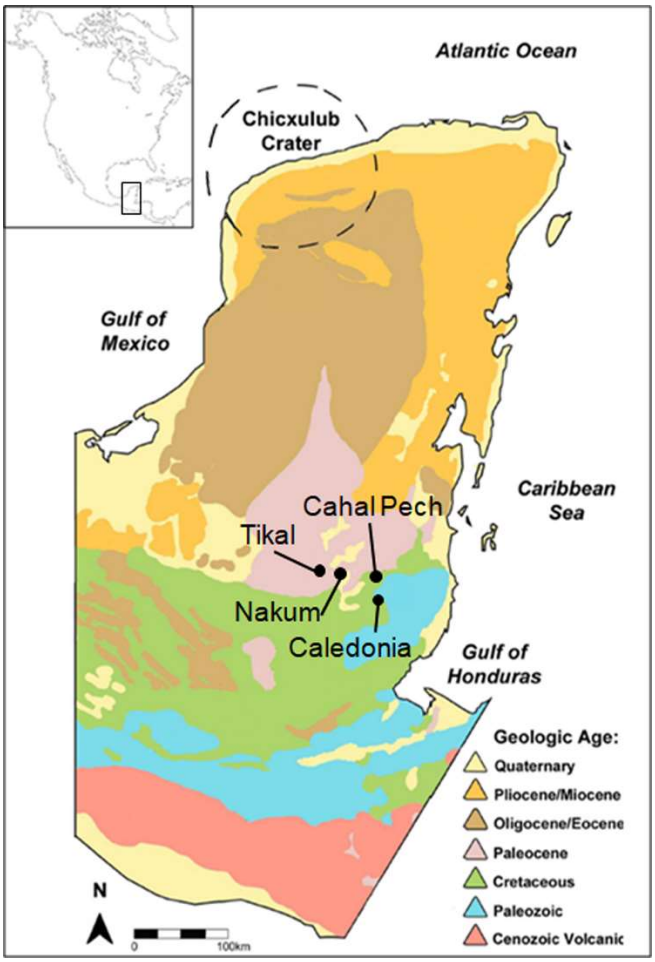

Figure 5.1: Geological map of the Maya region indicating the location of Nakum and other sites mentioned in the text (adapted from Sharpe et al. (2016) and the U.S. Geological Survey Geological Map of North America [Reed et al. 2005]).

above sea level, although partially modified terraces in the south and west areas of the site descend toward the Holmul River (Tozzer 1913).

The location of the site on the Holmul River facilitated human movement and riverine trade, as well as access to water and freshwater subsistence resources (Fig. 5.2). The presence of exotic marine materials at Nakum, including stingray spines from Burial 8 (Fig. 5.3) and Offering 9 (Źrałka et al. 2014), indicate the Holmul River was used to transport goods and likely people to the site (Hermes et al. 2006; Tozzer 1913; Źrałka and

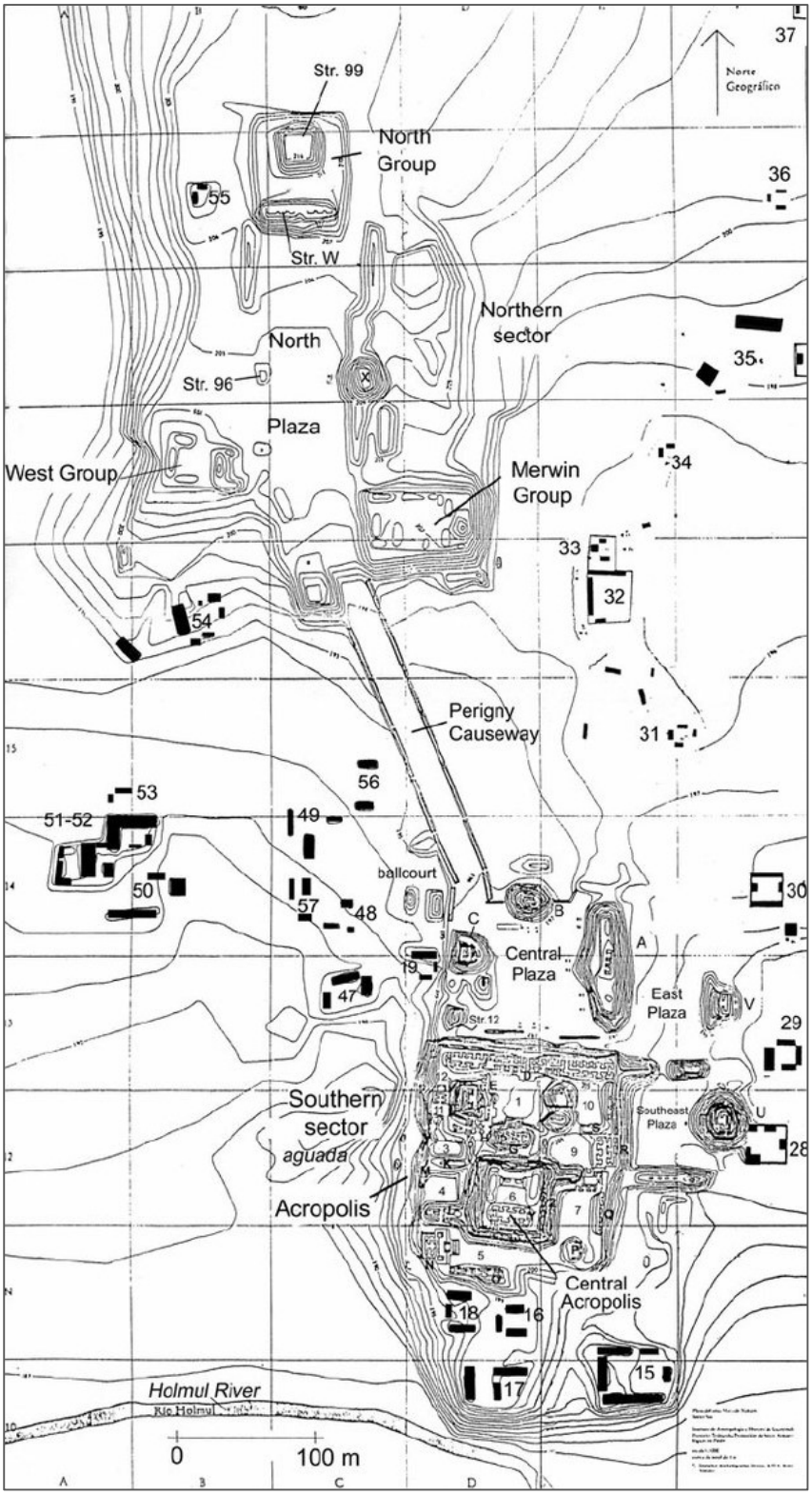

Figure 5.2: Map of Nakum located on the Holmul River illustrating the northern and southern sectors of the site (Źrałka and Hermes 2012:163).

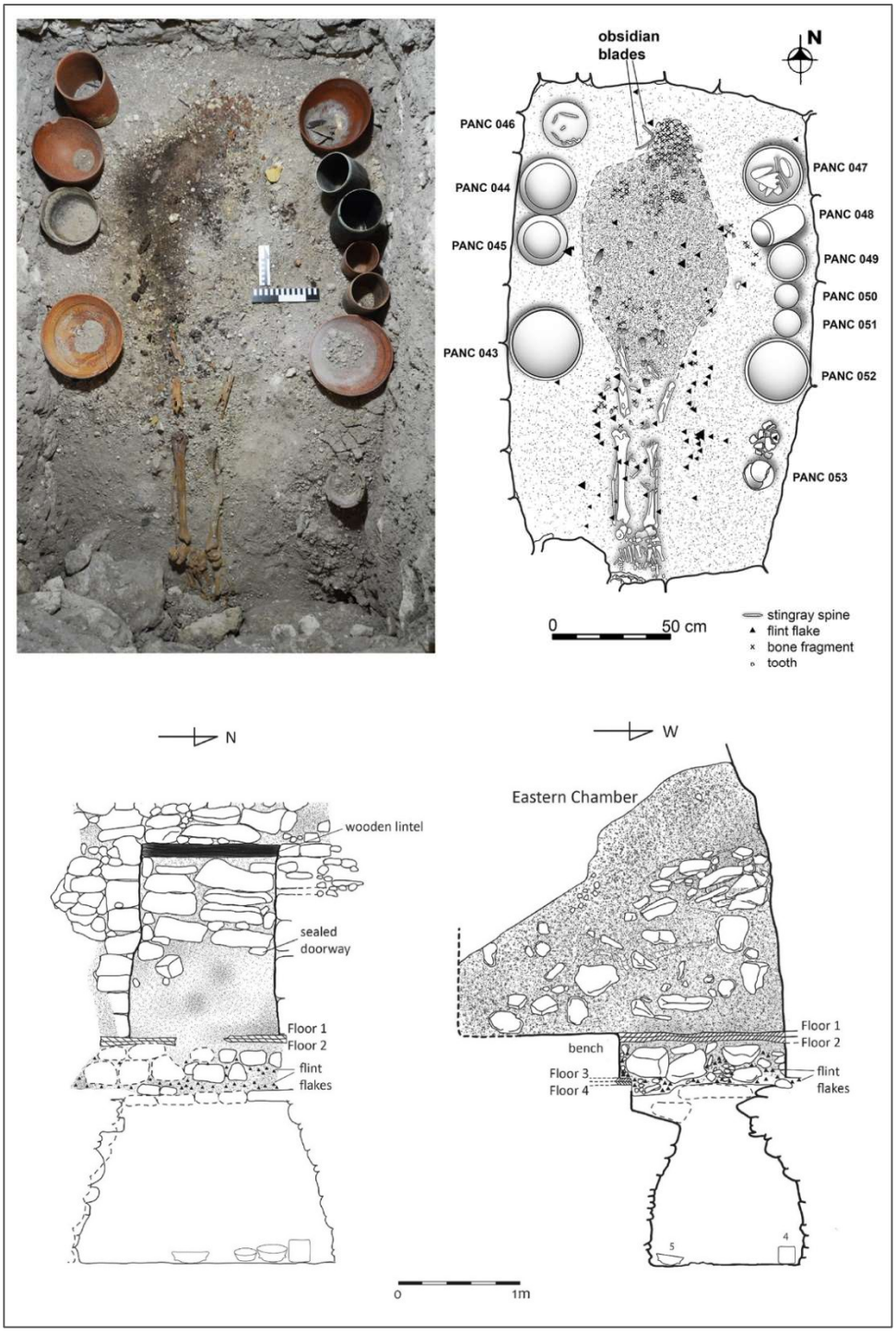

Figure 5.3: Plan and cross-section of Nakum Burial 8, an example of a richly furnished vaulted tomb located within a large pyramidal temple (Str. X), possibly the resting place of one of Nakum's kings who reigned during the transition from the Early to Late Classic periods (A.D. 500/550-600). Note the presence of stingray spines in vessel PANC046. Image courtesy of Dr. Jarosław Źrałka and the PAN.

Hermes 2012), as it is part of a larger trade network that connected sites from Central Peten to the Caribbean coast. The proximity of Nakum to the river also provided access to riverine subsistence resources, although the diet of the Nakum residents was most likely based on maize agriculture supplemented with other cultigens, wild plants, and animal resources, as was the case elsewhere in the Maya region (e.g., Price et al. 2018a; Rand et al. 2015b; Somerville et al. 2013; Tykot 2002; White 1999).

As at Tikal and other Maya sites (Braswell 2003; Price et al. 2010; Smyth and Rogart 2004; Wright et al. 2010), the presence of *talud-tablero* architecture in Nakum's South Sector, artifacts made from Central Mexican green obsidian, and locally made cylindrical tripod vessels have been interpreted as evidence of contact between people from Teotihuacan in Central Mexico and those at Nakum during the Early Classic period (Hermes et al. 2006; Koszkul et al. 2006; Źrałka and Koszkul 2007). Nearly all isotopic studies of Maya mobility have identified nonlocal individuals; however, the results suggest that long distance migration is less common than movement over short distances, with limited evidence that individuals from beyond the Maya region moved to Maya centres (Freiwald 2011a; Miller 2015; Patterson and Freiwald 2016; Price et al. 2008; Wright 2005a). This study assesses mobility to Nakum by comparing strontium and stable oxygen and sulfur isotope values in human tooth and bone to faunal baseline values that also serve to establish local and nonlocal foods in the diet and their potential contribution to human isotopic values.

5.2 Principles of Isotopic Analyses in Bioarchaeology

Stable isotopic analyses of diet are based on the premise that the $\delta^{13}C$, $\delta^{15}N$, and

δ^{34}S values of a consumer's tissues reflect those of their diet. Nitrogen and sulfur present in the organic portion of bone (i.e., collagen) are derived from dietary protein (Ambrose and Norr 1993; Richards et al. 2003; Tanz and Schmidt 2010; Webb et al. 2017). When protein consumption is adequate, carbon in collagen ($\delta^{13}C_{col}$) is derived primarily from dietary protein, whereas carbon in bone mineral (i.e., bioapatite; $\delta^{13}C_{ap}$) is derived from the whole diet (Ambrose and Norr 1993; Howland et al. 2003; Jim et al. 2004). Because bone remodels throughout life, $\delta^{13}C_{col}$, $\delta^{13}C_{ap}$, $\delta^{18}O_{ap}$, δ^{15}N, and δ^{34}S values will represent dietary averages from adolescence until the end of life. The rate of bone turnover does, however, vary depending on individual physiology and the bone sampled; for example, adult femoral cortical bone collagen can maintain isotopic values from foods consumed during adolescence (Hedges et al. 2007; Matsubayashi and Tayasu 2019). Unlike bone, tooth enamel does not remodel (Moradian-Oldak 2009), so its carbon, oxygen, and strontium isotope ($\delta^{13}C_{en}$, $\delta^{18}O_{en,}$ $^{87}Sr/^{86}Sr_{en}$) values reflect those of resources consumed when the enamel formed during childhood.

Stable carbon isotope analysis is used to differentiate the types of plants consumed by an individual. Most plants use the C_3 photosynthetic pathway and have an average δ^{13}C value of –26.5 ‰, whereas C_4 plants such as maize have an average value of –12.5 ‰ (O'Leary 1988; Smith and Epstein 1971). Although some plants use a third photosynthetic pathway (CAM) with intermediate values, it is unlikely they were consumed to any significant degree by the prehispanic lowland Maya (Powis et al. 1999; White 2005).

Terrestrial plants typically exhibit an average δ^{15}N value of +3 ‰, while those that directly fix nitrogen (i.e., legumes) have values close to 0 ‰ (Delwiche and Steyn 1970; Wada et al. 1975). Because δ^{15}N values increase between 3 ‰ and 6 ‰ at each trophic

level (Delwiche and Steyn 1970; Hedges and Reynard 2007; O'Connell et al. 2012), humans with an omnivorous diet will have elevated δ^{15}N values relative to those of prey animals from the same region. Likewise, nursing infants will have δ^{15}N values one trophic level above those of their mothers (Fuller et al. 2006). However, physiological factors such as pregnancy and disease can influence δ^{15}N values in human tissues (Fuller et al. 2004, 2005; Katzenberg and Lovell 1999; Nitsch et al. 2010; White and Armelagos 1997), and the δ^{15}N values throughout a region can vary by temperature, aridity, and proportion of soil nitrates (Ambrose 1991, 2000; Cormie and Schwarcz 1996; Heaton et al. 1986; Sealy et al. 1987; Somerville et al. 2018).

Stable sulfur isotope analysis has recently emerged as a promising technique for differentiating the consumption of terrestrial, freshwater, and marine dietary protein, and for identifying movement in prehistoric populations (Nehlich 2015; Rand and Nehlich 2018; Richards et al. 2001). Modern oceanic sulfate has a relatively uniform δ^{34}S value around +21 ‰ (Böttcher et al. 2007; Rees et al. 1978), whereas bedrock values vary based on rock type and age so that volcanic rocks exhibit an average δ^{34}S value around 0 ‰ and ocean evaporates (e.g., limestone) have higher values around +20 ‰ (Nehlich 2015). Because the δ^{34}S values of oceanic sulfate have fluctuated over time, the value of the inland Paleocene limestone surrounding Nakum is expected to be near +19 ‰ (Claypool et al. 1980). Although soil sulfate is primarily derived from bedrock weathering, atmospheric deposition may also occur (Bern and Townsend 2008). Sea spray, for example, causes coastal plants and their consumers up to 30 km inland to exhibit δ^{34}S values similar to those of marine resources (Gravenhorst 1978; Wakshal and Nielsen 1982).

Plants assimilate inorganic soil sulfate into the amino acids methionine and cysteine

(Brosnan and Brosnan 2006) and exhibit $\delta^{34}S$ values 1.5 ‰ lower than those of the environment in which they grow (Trust and Fry 1992). Animals must obtain methionine from dietary protein (Brosnan and Brosnan 2006; Ingenbleek 2006), and although the offset between the $\delta^{34}S$ values of consumer tissues and their dietary protein is thought to be minimal (+0.5 ± 2.4 ‰; Nehlich 2015:6; see also Krajcarz et al. 2019), the bone collagen of larger mammals may exhibit $\delta^{34}S$ values 1.5 ‰ lower than those of the foods they consume (Webb et al. 2017). Therefore, human $\delta^{34}S$ values should be lower than those in the local environment and values that are significantly different suggest that dietary protein was acquired from an isotopically distinct region and the individuals were therefore nonlocal (Nehlich 2015).

Stable oxygen isotope ($\delta^{18}O$) analysis is similarly useful for identifying nonlocal individuals (see Pederzani and Britton (2019) for a recent review). Drinking water $\delta^{18}O$ values are a function of the local climate, whereby higher values are associated with higher amounts of precipitation, increasing distance from the sea, higher altitudes, increasing humidity, and decreasing temperature (Rozanski et al. 1993). In the Maya region, the highest modern surface water $\delta^{18}O$ values come from the Peten Lakes region of Guatemala, followed by those along the Caribbean coast, while the lowest $\delta^{18}O$ values occur in the Highlands (Lachniet and Patterson 2009; Marfia et al. 2004). In general, higher values are found in the lowlands relative to the highlands, and the Yucatan has generally higher $\delta^{18}O$ values than those present in central or southwestern Mexico (Wassenaar et al. 2009). Although inhaled and consumed oxygen is also incorporated into body tissues, the $\delta^{18}O$ values in tooth enamel ($\delta^{18}O_{en}$) and bone apatite ($\delta^{18}O_{ap}$) primarily reflect those of water imbibed during childhood and in later in life, respectively (Longinelli 1984). Thus,

movement from an isotopically distinct region prior to death may be inferred if an individual's $\delta^{18}O$ values differ significantly from those of local drinking water sources. However, this may be complicated by growth-related stress (Warinner and Tuross 2010) and cultural practices such as cooking (Brettell et al. 2012), fermenting (Gagnon et al. 2015), or storing water (Scherer et al. 2015). Thus, it is best to interpret $\delta^{18}O$ values in conjunction with other isotopic assays (Pederzani and Britton 2019; Price et al. 2010).

Strontium isotope analysis measures the ratio between the stable isotope ^{86}Sr and the radiogenic isotope ^{87}Sr, which varies in the environment due to the age and composition of underlying geology (Faure and Powell 1972). Over time, rubidium-87 (^{87}Rb) in the Earth's crust decays into ^{87}Sr, causing older metamorphic rocks to have much higher $^{87}Sr/^{86}Sr$ values than younger volcanic rocks, while limestone exhibits intermediate values reflecting those of seawater at the time it formed (Bentley 2006; Hodell et al. 2004, 2007; Palmer and Elderfield 1985). In the Maya region, there is a gradual decrease in the range of limestone $^{87}Sr/^{86}Sr$ values from 0.7092 in the Eocene-Oligocene-Miocene-Pliocene carbonates of the northern and coastal Yucatan to 0.7071 in the Cretaceous and Paleocene limestones of the Southern Lowlands, while the volcanic rocks of the Guatemala Highlands and Pacific Coast to the south have much lower $^{87}Sr/^{86}Sr$ values between 0.7038 and 0.7050 (Hodell et al. 2004; Palmer and Elderfield 1985). The highest $^{87}Sr/^{86}Sr$ values occur in the Maya Mountains, where the metamorphic highlands contain pockets of relatively ancient rocks that have values that exceed 0.711 (Hodell et al. 2004; Freiwald 2011a).

Dietary strontium is primarily derived from plant foods, and substitutes for calcium in bone and tooth enamel bioapatite. Tooth enamel is the preferred sample material for strontium isotope analysis because strontium in bone is more susceptible to diagenetic

alteration (Hoppe et al. 2003). Because biological processes fractionate $^{87}Sr/^{86}Sr$ values below levels detectable by instrumentation, the ratios in human samples will represent those of the geological substrate from which food was acquired (Flockhart et al. 2015; Lewis et al. 2017). Thus, $^{87}Sr/^{86}Sr$ values from tooth enamel reflect those of the dietary catchment during the period in childhood when the tooth formed.

5.3 Materials and Methods

Pollution since the industrial revolution has altered modern $\delta^{34}S$ values, and so it is necessary to sample archaeological fauna to generate environmental baseline values for archaeological applications (Richards et al. 2001; Trust and Fry 1992). Therefore, eighteen archaeological faunal bone samples and one tooth (Table 5.1) recovered from Nakum were analyzed to provide isotopic baseline data. Nine archaeological human bones and seven teeth were also sampled, the contextual and biographical data of which can be found in Table 5.2. These samples come from multiple time periods and represent both higher status individuals interred in formal tombs (Burials 1 and 8) and crypts (Burials 2 and 5) and lower status individuals from an unfurnished grave (Burial 4) and a dedicatory burial (Burial 7), as well as isolated elements from varying contexts (see Table 5.2). Age and sex estimations (Table 5.2) were conducted by Matute using standard techniques (Buikstra and Ubelaker 1994). Poor preservation dictated the sampling of the most well-preserved elements from each context.

Each specimen was thoroughly cleaned and dried prior to preparation (see Appendix A for details). Bone collagen was extracted following standard procedures (Honch et al. 2006; Nehlich and Richards 2009; Rand et al. 2015a), details of which can

Table 5.1: Contextual, species, and biographical data for the Nakum fauna samples.

Lab #	Sample ID	Context	Common Name	Taxon	Age	Element	Period
4315	MOF4	VI-20-3-3	cf. White-tailed deer	cf. *Odocoileus virginianus*	Adult	Ulna	Terminal Classic
4316	MOF10	VI-21-6-2	cf. White-tailed deer	cf. *Odocoileus virginianus*	Adult	Left humerus	Terminal Classic
4317	MOF1	III-5-2-2	cf. White-tailed deer	cf. *Odocoileus virginianus*	Adult	Metacarpal	Late to Terminal Classic
4318	MOF11	VI-22-5	Mesoamerican slider	*Trachemys venusta*	Adult	Femur	Terminal Classic
4319	MOF14	VI-4-2-4	cf. White-tailed deer	cf. *Odocoileus virginianus*	Adult	Metacarpal	Late Classic
4320	MOF9	VI-28-8-4	cf. White-tailed deer	cf. *Odocoileus virginianus*	Adult	Tibia	Terminal Classic
4321	MOF18	XXII-3-3	cf. White-tailed deer	cf. *Odocoileus virginianus*	Adult	Metatarsal	Late Classic
4322	MOF6	VI-22-5	Deer	Capreolinae	Subadult	Mandible	Terminal Classic
4323	MOF12	VI-12-1	cf. White-tailed deer	cf. *Odocoileus virginianus*	Adult	Tibia	Late Classic
4324	MOF3	VI-22-1-7	Deer	Capreolinae	Adult	Mandible	Late Classic
4325	MOF15	VI-2-6	cf. White-tailed deer	cf. *Odocoileus virginianus*	Adult	Metapodial	Late Classic
4326	MOF16	VI-31A-12-3	cf. White-tailed deer	cf. *Odocoileus virginianus*	Adult	Long bone	Early Classic
4327	MOF13	VI-6A-2	Brocket deer	*Mazama* sp.	Adult	Calcaneus	Protoclassic
4328	MOF8	VI-28-2-7	cf. White-tailed deer	cf. *Odocoileus virginianus*	Adult	Left ilium	Terminal Classic
4329	MOF17	XIII-3-1-9	cf. White-tailed deer	cf. *Odocoileus virginianus*	Adult	Scapula	Terminal Classic
4330	MOF5	VI-22-5-1	Turkey	*Meleagris* sp.	Adult	Tibiotarsus	Terminal Classic
4331	MOF2	VI-20-2-5	Deer	Capreolinae	Adult	Metacarpal	Terminal Classic
4332	MOF7	VI-20-2-4	Deer	Capreolinae	Adult	Metacarpal	Late Classic
4495	PANE3	I-12-3-9	Dog	*Canis familiaris*	Adult	Left carnassial	Middle Preclassic

be found in Appendix A. For stable carbon and nitrogen isotope analysis, samples were analyzed using a Thermo Scientific Delta V Plus I Gas Source Isotope Ratio Mass Spectrometer (IRMS) coupled via continuous flow to a Carlo Erba NA 1500 Series II Elemental Analyzer (EA) in the CREAIT Network's Stable Isotope Laboratory (SIL) at Memorial University of Newfoundland (MUN) (see Appendix A). Analytical precision and accuracy were calculated following the technique outlined in Szpak et al. (2017a) and

Table 5.2: Contextual and biographical data of the Nakum human samples.

Burial #	Burial Type	Context	Structure	Time Period	Age	Sex	Sampled Element	PANE #	Lab #
1	Tomb	V-3-8 con 1	15	Late Classic	35-45 years	Indeterminate	Long Bone	17	4509
							Left M_1	11	4503
2	Crypt	VI-3A-10	15	Protoclassic	Adult	Female	Femur	15	4507
							Left P^4	13	4505
4	Unfurnished	I-14	X	Terminal Classic	4-6 years	Indeterminate	Right Ulna	5	4497
5	Crypt	I-2A	X	Early Classic	Adult	Probable Female	Right Tibia	7	4499
							Right M_1	2	4494
7	Dedicatory	I-13	X, In front of façade	Middle to Late Preclassic	Adult	Indeterminate	Long Bone	6	4498
							Left M_2	1	4492
8	Tomb	I-6B-1-7 sector 3	X	Early Classic	YA to MA	Indeterminate	Femur	23	4517
							LC^1	22	4515
N/A	N/A	III-1-2	99	Terminal Classic	Adult	Indeterminate	Ulna/Radius	8	4500
N/A	N/A	IV-4-5-2	W	Terminal Classic	Adult	Indeterminate	Right M^2	9	4501
N/A	N/A	VI-6A-1	14, Core of SW portion	Late Preclassic or Early Classic	Adult	Indeterminate	Right Humerus	14	4506
N/A	N/A	VI-31A-11-3	G, Core of *talud-tablero* platform	Early Classic	Subadult	Indeterminate	Left m^2	16	4508
N/A	N/A	VI-8-14A	14, Hidden Building	Early Classic	Adult	Indeterminate	Left Patella	20	4511

Note: M = molar, P = premolar, C = Canine, I = incisor, C, subscript numbers = mandibular dentition, superscript = maxillary dentition, lower case = deciduous dentition

details can be found in Appendices A and C. Analytical precision was ±0.21 ‰ for $\delta^{13}C$ and ±0.16 ‰ for $\delta^{15}N$ based on repeated measurements of calibration standards, check standards, and sample replicates (see Appendix C). Analytical accuracy was ±0.21 ‰ for $\delta^{13}C$ and ±0.20 ‰ for $\delta^{15}N$ based on the difference between the observed and known $\delta^{13}C$ and $\delta^{15}N$ values of the check standards and their long-term standard deviations (Appendix C). Considering both analytical accuracy and precision, the standard uncertainty[11] was ±0.30 ‰ for $\delta^{13}C$ and ±0.25 ‰ for $\delta^{15}N$ (Appendix C).

Stable sulfur isotopes were analyzed on a Thermo Scientific Delta V Plus IRMS coupled via continuous flow to a Costech EA (ECS4010) at the Stable Isotope Laboratory in the Department of Earth and Planetary Sciences, University of Tennessee Knoxville (see Appendix A). Analytical precision was ±1.00 ‰, although analytical accuracy could not be calculated as check standards were not included in the analysis (Szpak et al. 2017a; Appendix C).

Bioapatite was isolated from powdered bone and tooth enamel samples following standard procedures (Garvie-Lok et al. 2004) and stable carbon and oxygen isotopes were analyzed on a Thermo Scientific Delta V IRMS coupled to a Gas Bench via a continuous-flow interface in the CREAIT Network's SIL facility at MUN (Appendix A). Using the method of Szpak et al. (2017a) and data provided in Appendix C, the measurement precision was ±0.16 ‰ for $\delta^{13}C$ and ±0.31 ‰ for $\delta^{18}O$ and analytical accuracy was ±0.08 ‰ for $\delta^{13}C$ and ±0.09 ‰ for $\delta^{18}O$. Considering both precision and accuracy, the overall standard uncertainty was ±0.18 ‰ for $\delta^{13}C$ and ±0.32 ‰ for $\delta^{18}O$.

[11] In Rand et al. (2020a), the analytical accuracy (u_c) and measurement precision (s_{srm}), which is calculated from the calibration and check standards, were reported to be consistent with earlier studies.

Strontium was extracted from one faunal and three human teeth samples using ion-exchange chromatography (Copeland et al. 2008; Madgwick et al. 2017), and details can be found in Appendix A. Enamel was sampled because it is resilient against postmortem chemical alteration (i.e., diagenesis) and so will accurately reflect the $^{87}Sr/^{86}Sr$ values during life. The $^{87}Sr/^{86}Sr$ values of tooth dentine were also analyzed as proxies for the local range of values because dentine is more susceptible to diagenetic uptake of soil-derived strontium (Budd et al. 2000) and therefore is assumed to reflect local soluble strontium in the burial environment (Montgomery et al. 2007). All purified Sr solutions were analyzed on a Thermo Scientific Neptune™ multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) within the Micro Analysis Facility (MAF) of CREAIT at MUN along with the analytical standard NIST SRM 987, procedural standards, and blanks. The deviation of the average value for SRM 987 during the analytical session was used to correct all sample values (see Appendix A). Finally, the signal intensities of total procedural blanks were considered negligible (<0.1 %) when compared to the typical ^{88}Sr intensities of the samples and standards.

Isotopic values that fell beyond the interquartile range (IQR) multiplied by 1.5 subtracted from the first quartile and added to the third of the data set were interpreted as nonlocal individuals. These outlying values were removed prior to calculating local isotopic baseline values as falling within two standard deviations of the mean of the trimmed data set (see Appendix A). All statistical analyses were performed in SPSS version 25 for Windows (IBM®). Due to small sample sizes and the nonparametric distribution of the data, statistical differences and correlations between sample values were tested using

nonparametric statistical tests interpreted at the 95% significance level (i.e., $p = 0.05$) (see Appendix A for more detail).

5.4 Results

The average $\delta^{13}C_{col}$ (–21.1 ± 0.9 ‰) and $\delta^{15}N$ (+5.6 ± 1.2 ‰) values of the 16 faunal remains with collagen sufficiently preserved for interpretation (Ambrose 1990; DeNiro 1985; Nehlich and Richards 2009; van Klinken 1999) indicate that the majority of the animals consumed C_3-based diets typical of deer, turtles, and wild turkeys in the Maya region (Table 5.3; Fig. 5.4). The turkey's $\delta^{13}C_{col}$ (–21.3 ‰) and $\delta^{15}N$ (+6.1 ‰) values fall within the range of the terrestrial mammals (i.e., deer), suggesting it consumed a terrestrial C_3-based diet. The Mesoamerican slider turtle's negative $\delta^{13}C_{col}$ value (–22.6 ‰) reflects a C_3-based diet, with an elevated $\delta^{15}N$ value (+7.5 ‰) that indicates the consumption of fish, other turtles, and invertebrates. When the turtle's elevated $\delta^{15}N$ value is excluded, the average fauna $\delta^{15}N$ value (+5.4 ± 1.1 ‰) suggests that the remaining specimens were herbivores, as expected based on the species identifications.

Table 5.3 presents the results from the five human collagen samples that were preserved well enough for analysis (Ambrose 1990; DeNiro 1985; Nehlich and Richards 2009; van Klinken 1999). Due to differences in preparation and analysis (see Pestle et al. 2014), the $\delta^{13}C$ and $\delta^{15}N$ values previously obtained by Matute (unpublished data) are included in Table 5.3 but were excluded from statistical analyses and interpretations. The average human $\delta^{13}C$ value (–11.6 ± 2.2 ‰; Table 5.3, Fig. 5.4) is significantly more positive than that of the fauna ($U = 0.000$, $p = 0.001$), demonstrating the importance of C_4 plants, probably maize, in the Nakum diet. These individuals also relied on terrestrial animal

protein, given that their average δ^{15}N value (+10.2 ± 1.0 ‰; Fig. 5.4, Table 5.3) is significantly elevated relative to that of the fauna ($U = 0.000$, $p = 0.001$).

Due to potential diagenetic alteration, only the carbonate data from the five bone samples that yielded sufficient collagen for analysis are considered in this study (Table 5.3, Fig. 5.5). This is because the preservation of collagen and apatite are linked (Kendall et al. 2018), and samples that lacked collagen in this study had significantly higher $\delta^{13}C_{ap}$ values than those with well-preserved collagen ($U = 0.000$, $p = 0.014$). This suggests that samples with poorly preserved collagen were diagenetically contaminated by exogenous carbon enriched in ^{13}C, and so they were removed from the following interpretations. The human bone $\delta^{13}C_{ap}$ values of the five samples with well preserved collagen (–7.6 ± 1.3‰; see Table 5.3) is consistent with a whole diet dependent on maize but also supplemented with C_3-based foods.

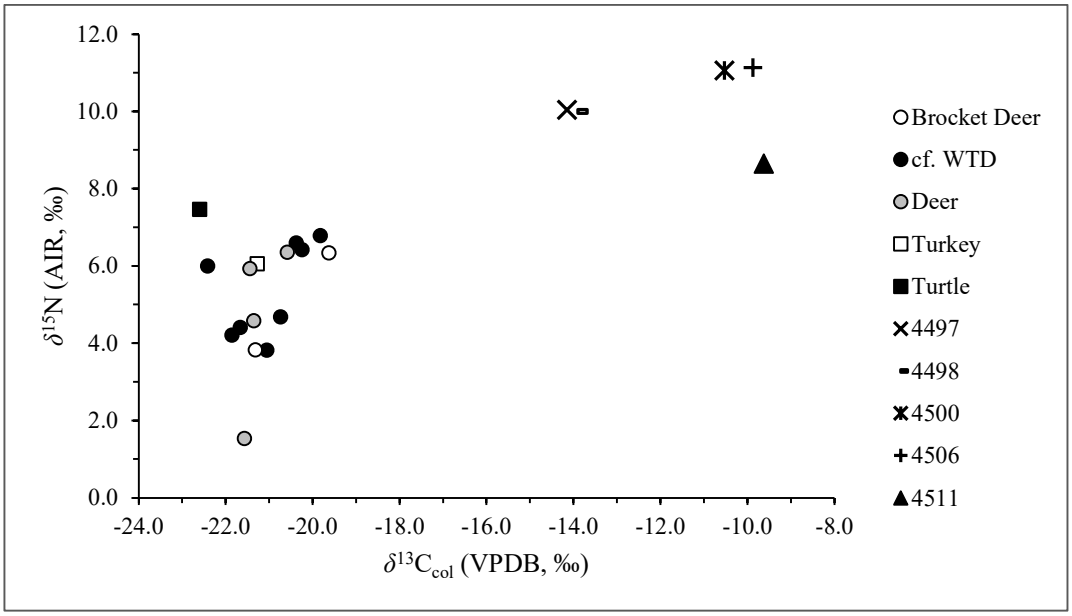

Figure 5.4: The δ^{13}C and δ^{15}N values of the fauna and human bone collagen from Nakum. Humans are identified by laboratory number whereas fauna are identified by species. Note: WTD = white-tailed deer.

Table 5.3: Stable carbon, nitrogen, sulfur, and oxygen isotope, concentration, and quality data from bone samples.

Lab #	Context/ Species	$\delta^{13}C_{col}$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VDCT, ‰)	$\delta^{13}Cap$ (VPDB, ‰)	$\delta^{18}O$ (VPDB, ‰)	Collagen Yield (%)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S
Humans													
4509	Burial 1	-	-	-	−5.2[a]	−4.5[a]	*0.0*	-	-	-	-	-	-
4507	Burial 2	−9.1*	+10.0*	-	−5.7[a]	−5.0[a]	1.0	41.8	15.0	0.2	3.3	533.3	164.1
4497	Burial 4	−14.2	+10.0	+13.4	−8.7	−5.1	1.5	42.0	14.7	0.2	3.3	492.1	148.1
4499	Burial 5	−8.2*	+9.4*	-	−4.9[a]	−5.3[a]	*0.0*	-	-	-	-	-	-
4498	Burial 7	−13.9	+10.0	+13.1	−8.9	−4.6	1.2	42.2	15.0	0.2	3.3	546.9	163.4
4517	Burial 8	-	-	-	−3.8[a]	−4.6[a]	*0.0*	-	-	-	-	-	-
4511	Hidden Building, Str. 14	−9.6	+8.7	+12.9	−6.1	−4.6	2.0	43.3	15.8	0.3	3.2	462.5	145.6
4500	Str. 99	−10.5	+11.1	+13.3	−7.9	**−8.7**	1.9	42.9	15.3	0.2	3.3	620.0	189.9
4506	Core of Str. 14	−9.9	+11.1	+12.9	−6.3	−4.1	*0.2*	-	-	-	-	-	-
$\bar{x} \pm \sigma$ (n)		−11.6 ± 2.2 (5)	+10.2 ± 1.0 (5)	+13.1 ± 0.2 (5)	−7.6 ± 1.3 (5)	−5.4 ± 1.9 (5)	0.9 ± 0.8 (9)	42.4 ± 0.6 (5)	15.2 ± 0.4 (5)	0.2 ± 0.04 (5)	3.3 ± 0.04 (5)	531 ± 60(5)	162 ± 18 (5)
Fauna													
4315	cf. *Odocoileus virginianus*	−21.3	+3.8	+14.4	-	-	3.4	46.3	16.5	0.2	3.3	582.1	178.3
4316	cf. *Odocoileus virginianus*	**-**	**-**	**-**	**-**	**-**	*0.3*	**-**	**-**	**-**	**-**	**-**	**-**
4317	cf. *Odocoileus virginianus*	−21.7	+4.4	+14.5	-	-	4.3	45.9	16.3	0.2	3.3	665.5	201.9
4318	*Trachemys venusta*	−22.6	+7.5	+14.6	-	-	4.7	46.1	16.4	0.2	3.3	706.2	215.4
4319	cf. *Odocoileus virginianus*	−22.4	+6.0	+14.4	-	-	5.2	47.2	16.8	0.2	3.3	561.5	171.0
4320	cf. *Odocoileus virginianus*	−20.3	+6.4	+13.4	-	-	2.8	44.4	15.6	0.2	3.3	559.0	167.9
4321	cf. *Odocoileus virginianus*	-	-	-	-	-	*0.0*	-	-	-	-	-	-
4322	Capreolinae	−21.6	+1.5[b]	+12.8	-	-	5.0	45.2	15.8	0.2	3.3	565.6	169.0
4323	cf. *Odocoileus virginianus*	−21.1	+3.8	+13.1	-	-	3.4	43.6	15.2	0.2	3.3	595.7	178.2
4324	Capreolinae	−20.6	+6.4	+12.5	-	-	4.5	45.3	16.3	0.2	3.2	610.0	187.9

Table 5.3: Continued.

Lab #	Context/ Species	$\delta^{13}C_{col}$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VDCT, ‰)	$\delta^{13}Cap$ (VPDB, ‰)	$\delta^{18}O$ (VPDB, ‰)	Collagen Yield (%)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S
4325	cf. *Odocoileus virginianus*	–20.4	+6.6	**+5.0**[b]	-	-	5.5	46.5	16.6	0.3	3.3	375.8	115.0
4326	cf. *Odocoileus virginianus*	–19.8	+6.8	+13.5	-	-	3.4	47.1	16.6	0.2	3.3	587.0	177.2
4327	*Mazama* sp.	–19.6	+6.3	+12.9	-	-	2.9	44.1	15.7	0.2	3.3	602.5	183.8
4328	cf. *Odocoileus virginianus*	–20.7	+4.7	+14.4	-	-	3.7	45.5	16.1	0.2	3.3	569.1	172.9
4329	cf. *Odocoileus virginianus*	–21.9	+4.2	+13.0	-	-	3.7	45.6	16.3	0.2	3.3	528.8	162.3
4330	*Meleagris* sp.	–21.3	+6.1	+14.0	-	-	3.4	45.1	15.6	0.2	3.4	525.3	155.7
4331	Capreolinae	–21.4	+4.6	+13.8	-	-	3.5	46.4	16.4	0.2	3.3	638.1	193.6
4332	Capreolinae	–21.4	+5.9	+14.0	-	-	3.3	45.3	16.4	0.2	3.2	656.4	203.1
$\bar{x} \pm \sigma$ (n)		–21.1 ± 0.9 (16)	5.3 ± 1.5 (15)	13.7 ± 0.7 (15)	-	-	3.5 ± 1.4 (18)	45.4 ± 1.3 (16)	16.1 ± 0.6 (16)	0.2 ± 0.04 (16)	3.3 ± 0.04 (16)	583 ± 74 (16)	177 ± 23 (16)

Note: Italicized values fall beyond acceptable quality parameters and were excluded from further analysis. Bolded values are statistical outliers and are interpreted as nonlocal.
*Values from Matute (unpublished data)
[a] Bone values removed from interpretation due to suspected diagenetic alteration.
[b] Values were removed from the calculation of $\bar{x}\pm s$ because they fall beyond $2s$ of $\bar{x}$.

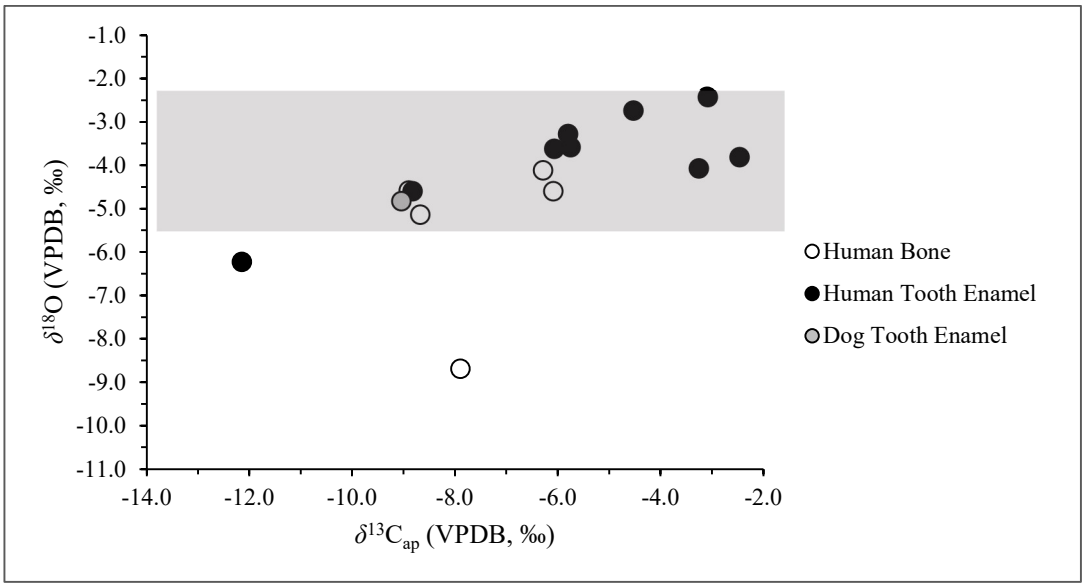

Figure 5.5: The $\delta^{13}C_{ap}$ and $\delta^{18}O_{ap}$ values of bone and tooth enamel samples from Nakum. The shaded area represents the local range of $\delta^{18}O$ values determined from the mean and two standard deviations of all human enamel and bone samples with viable collagen excluding the two outliers ($\bar{x} \pm 2\sigma = -3.9 \pm 1.6$ ‰).

Maize appears to have been an important component of childhood diet as well, as most individuals had $\delta^{13}C_{en}$ values that were elevated relative to the single dog tooth (–9.1 ‰; Table 5.4, Fig. 5.5), suggesting the consumption of maize when their teeth formed. However, the $\delta^{13}C_{en}$ value from Burial 7 (–8.8 ‰) and that of sample 4508 (–12.2 ‰) are more negative, suggesting more C_3-based foods in the childhood diets of these individuals. The human bone $\delta^{13}C_{ap}$ values are more negative than those of the teeth (Fig. 5.5), which may indicate differential fractionation of carbon isotopes during incorporation into the apatite of bones and teeth, differences in maize consumption from childhood to adulthood, or possible diagenetic alteration of the bone values. The last possibility is unlikely, however, as the $\delta^{13}C$ values of the five well-preserved human collagen and apatite samples are significantly positively correlated ($r_s = 0.9000$, $p = 0.037$), indicating a shared source of carbon (i.e., maize).

Table 5.4: Stable carbon, oxygen, and strontium isotope data from Nakum tooth samples.

Lab #	Burial #, Location, or Species	$\delta^{13}C_{en}$ (VPDB, ‰)	$\delta^{18}O_{en}$ (VPDB, ‰)	$^{87}Sr/^{86}Sr_{en}$	$^{87}Sr/^{86}Sr_{d}$
4503	1	−3.1	−2.4	0.7085	0.7082
4505	2	−4.5	−2.7	0.7082	0.7081
4494	5	−2.5	−3.8	-	-
4492	7	−8.8	−4.6	-	-
4515	8	−3.3	−4.1	0.7084	0.7081
4501	Str. W	−5.8	−3.6	-	-
4508	Str. G	−12.2	**−6.2**	-	-
4495*	*Canis familiaris*	−9.1	−4.9	0.70789	0.70795
$\bar{x} \pm \sigma$ (n)		−5.7 ± 3.6 (7)	−3.9 ± 1.3 (7)	0.7084 ± 0.0002 (3)	0.7081 ± 0.00003 (3)

Note: Bolded values are statistical outliers and are interpreted as nonlocal. Lower case "en" indicates enamel whereas the lower case "d" represents dentine.
*The dog values were not included in the calculation of the mean and standard deviation.

The archaeological faunal $\delta^{34}S$ values provide new isotopic information in Mesoamerica and suggest that at least one animal was acquired nonlocally. The average $\delta^{34}S$ value of 16 faunal specimens was relatively uniform (+13.7 ± 0.7 ‰; Table 5.3, Fig. 5.6) and shows that they obtained sulfur in dietary protein from the local environment. However, the $\delta^{34}S$ value of +5.0 ‰ for an ungulate metapodial consistent with that of a white-tailed deer (4325, cf. *Odocoileus virginianus*) was significantly lower, suggesting it was imported to the site. The human $\delta^{34}S$ values were not significantly different from those of the fauna excluding the outlier (U = 29.500, p = 0.385; Fig. 5.6), indicating that the humans consumed local animal protein in the years prior to their deaths.

The dog and three human teeth also have local $^{87}Sr/^{86}Sr$ values (Table 5.4). The $^{87}Sr/^{86}Sr$ values of the dog tooth enamel (0.7079) and dentine (0.7080) are only slightly lower than the mean $^{87}Sr/^{86}Sr$ enamel and dentine values of Burials 1, 2, and 8 (0.7084 ±

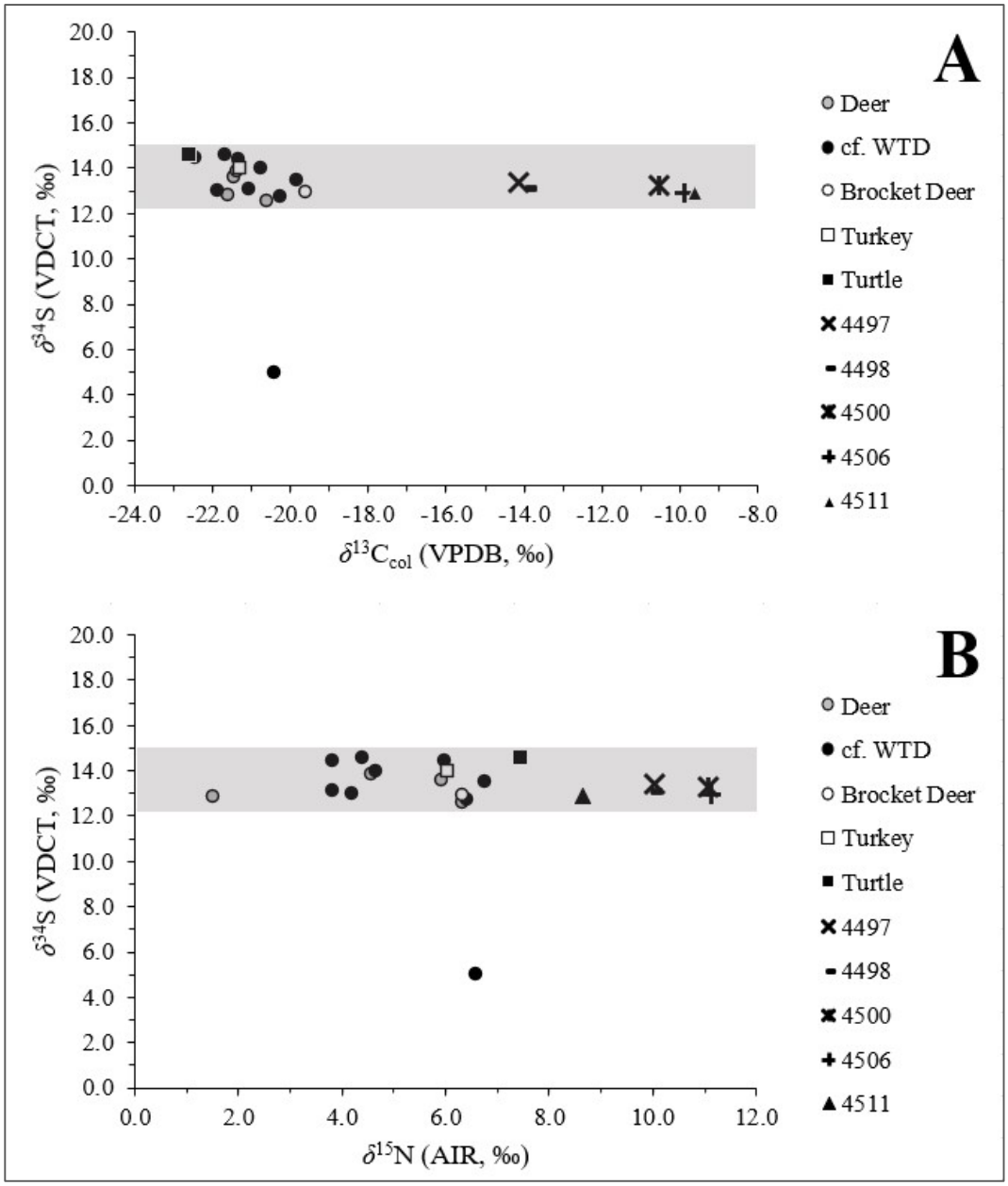

Figure 5.6: Human and faunal $\delta^{34}S$ values relative to (A) $\delta^{13}C$ and (B) $\delta^{15}N$ values from the same individual. Humans are identified by Lab # whereas fauna are identified by species. The shaded area represents the local range of $\delta^{34}S$ values as determined from the faunal data ($\bar{x} \pm 2\sigma = +13.6 \pm 1.4$ ‰).

0.0002 and 0.7081 ± 0.00003, respectively; Fig. 5.7). Although these values are higher than those of the rock, plant, water, and soil samples in the Central Lowlands, recorded by

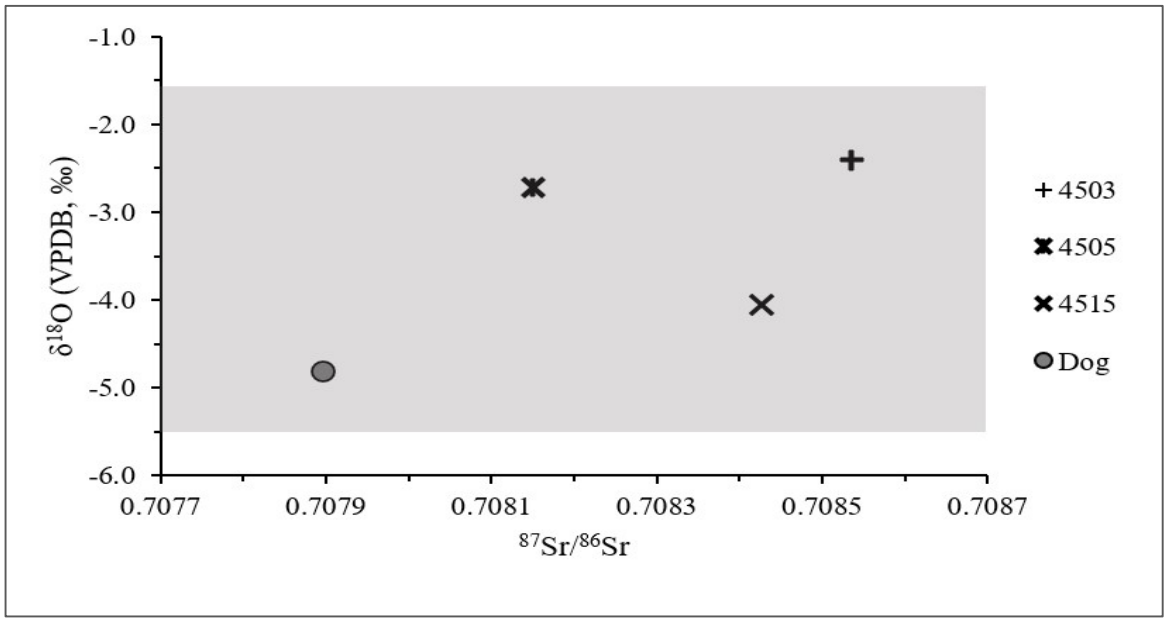

Figure 5.7: The $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values of three human and one canine tooth enamel samples from Nakum. The shaded area represents the local range of $\delta^{18}O$ values (see text and Fig. 5.5 for details) and does not reflect local $^{87}Sr/^{86}Sr$ values.

Hodell and colleagues (2004), they are similar to biologically available $^{87}Sr/^{86}Sr$ values identified at San Bartolo (Davies 2012), Naranjo (Freiwald et al. 2014), and many other sites to the east (Freiwald 2011a; Sutinen 2014), suggesting the Nakum individuals represent a local population that mainly consumed local resources during childhood.

The $\delta^{18}O_{en}$ results (Table 5.4) support this interpretation and suggest that most individuals drank local water during childhood, although there are two statistical outliers (Fig. 5.5). The average values of human bone (–5.4 ± 1.9 ‰) were lower than those of the teeth (–3.9 ± 1.3 ‰), which likely reflects the incorporation of oxygen from milk enriched in ^{18}O into the teeth while the enamel formed during breastfeeding (Wright and Schwarcz 1998, 1999). Although $\delta^{18}O$ values are species-specific (Iacumin et al. 1996; Longinelli 1984), that of the dog tooth enamel (–4.9 ‰) is intermediate to the average values of human

bones and teeth, all of which are consistent with values of water sources and human tissues from Central Lowland Maya sites (Freiwald 2011a; Lachniet and Patterson 2009; Marfia et al. 2004; Price et al. 2010). However, although all bone and enamel $\delta^{18}O$ values fell within two standard deviations of their respective mean values, when the enamel and bone values are pooled (–4.4 ± 3.1‰), the $\delta^{18}O_{ap}$ of –8.7 ‰ from an isolated ulna/radius (4500) excavated from a Terminal Classic termination ritual at the summit of Str. 99 falls beyond this range. When this outlier is removed, the $\delta^{18}O_{en}$ value from an isolated deciduous left second mandibular molar recovered from the core of the Early Classic Str. G *talud-tablero* platform (4508, –6.2 ‰) falls beyond two standard deviations of the adjusted mean. Therefore, the local $\delta^{18}O$ range for Nakum was determined as falling within two standard deviations of the mean of the pooled human bone and enamel $\delta^{18}O$ values after the two outlying values were removed (–3.9 ± 1.6 ‰; after Wright 2005a; see Fig. 5.5), and the individuals removed from the analysis are interpreted as nonlocal.

5.5 Discussion

5.5.1 Diet at Prehispanic Nakum

The average faunal $\delta^{13}C$ values indicate the consumption of C_3-based protein regardless of genus and species and is consistent with the average values of archaeological C_3 browsers elsewhere in the Maya region (Emery et al. 2000; Emery and Thornton 2008). Interestingly, one deer had a much lower $\delta^{15}N$ value, which could be explained by the consumption of large amounts of legumes, plants that directly fix atmospheric nitrogen and so have low $\delta^{15}N$ values relative to non-nitrogen-fixing plants (Delwiche and Steyn 1970). The turkey's $\delta^{13}C_{col}$ and $\delta^{15}N$ values (–21.3 ‰ and +6.1 ‰, respectively) fall among those

of the mammals (i.e., deer), indicating a terrestrial diet. The turkey's low $\delta^{13}C_{col}$ also suggests it was probably wild, as domesticated turkeys at other Maya sites have been found to have isotopic values comparable to those of humans due to the consumption of maize (i.e., elevated $\delta^{13}C$ and $\delta^{15}N$ values; Sharpe et al. 2018; Thornton et al. 2016).

The Nakum faunal $\delta^{34}S$ values were surprisingly elevated relative to those from inland sites elsewhere in the world and approach values expected in marine or coastal environments (i.e., greater than +14‰; Nehlich and Richards 2009; Richards et al. 2001). Similarly elevated $\delta^{34}S$ values at Thebes, Greece (Vika 2009), and Romiot, Italy (Craig et al. 2010) have been attributed to the underlying limestone geology, which is derived from marine evaporates that reflect the $\delta^{34}S$ values of oceanic sulfate at their time of formation (Claypool et al. 1980). It also appears that any sulfur deposited from atmospheric sources with lower $\delta^{34}S$ values (i.e., volcanic ash fall; Tankersley et al. 2016) has been obscured by values derived from the limestone bedrock. Thus, the narrow range of faunal $\delta^{34}S$ values from Nakum (excluding the outlying value of +5.0 ‰ from 4325) indicate a shared source of dietary sulfur obtained from plants that assimilated inorganic sulfate from the limestone soils surrounding the site.

Interestingly, although the Mesoamerican slider (*Trachemys venusta*) exhibited a $\delta^{34}S$ value (+14.6 ‰) similar to that of the terrestrial animals, it has elevated $\delta^{15}N$ (+7.5 ‰) and low $\delta^{13}C_{col}$ (–22.6 ‰) values that are indicative of a freshwater diet. This is because freshwater ecosystems have more negative $\delta^{13}C$ values and more trophic levels than terrestrial ecosystems, which lead to elevated $\delta^{15}N$ values in higher-order animals (Guiry 2019; Winemiller et al. 2011). This genus is, however, an opportunistic feeder, omnivorous on both land and water, and its diet may vary by age and sex (Bouchard and Bjorndal 2005;

Dreslik 1999). Therefore, the elevated $\delta^{13}C$ value of this individual may instead reflect a diet based on terrestrial C_3 plants influenced by the "canopy effect", wherein recycled CO_2 causes more negative $\delta^{13}C$ values (van der Merwe and Medina 1991). Although differential $\delta^{34}S$ values have been used to distinguish terrestrial from freshwater diets elsewhere (Drucker et al. 2018b; Nehlich et al. 2010), the values from these ecosystems may also overlap (Privat et al. 2007). Therefore, although the turtle's $\delta^{34}S$ value is indistinguishable from those of the terrestrial animals, it is not possible to determine whether it consumed a mainly terrestrial or freshwater diet without additional freshwater baseline $\delta^{34}S$ values.

As at other Maya sites (see Somerville et al. 2013), elevated $\delta^{13}C$ from both the apatite and collagen of the five human bone samples indicate the Nakum Maya consumed maize, supplemented with C_3 plants, whereas the elevated $\delta^{15}N$ values relative to those of the sampled fauna suggest the consumption of animal protein. While the average human $\delta^{13}C$ values from Nakum are somewhat more negative than elsewhere in the Maya lowlands, there exists variation over time and space, as well as among elite and non-elite populations, among other variables (Ebert et al. 2019; Freiwald 2011a; Gerry 1993; Somerville et al. 2013). At Nakum, for example, there are differences in the source of dietary protein, as the individuals from Burials 4 (4497) and 7 (4498) likely consumed more C_3-based animal protein, as evidenced by their relatively lower $\delta^{13}C_{col}$ values and elevated $\delta^{15}N$ values. Conversely, an isolated ulna/radius from Str. 99 (4500) and an isolated humerus from Str. 14 (4506) had elevated $\delta^{13}C_{col}$ values and consumed C_4-based protein, possibly from animals that consumed maize, as they had the highest $\delta^{15}N$ values at Nakum. Finally, an isolated patella recovered form the Hidden Building in Str. 14 (4511) with

similarly elevated $\delta^{13}C_{col}$ values has a $\delta^{15}N$ value nearly a trophic level below the other two, indicating the direct consumption of maize protein.

Interestingly, it appears as though sulfur in the Nakum Maya bone collagen samples was derived from maize rather than animal protein. Because nitrogen is derived from multiple amino acids and reflects animal consumption (Hare et al. 1991), a correlation between the $\delta^{15}N$ and $\delta^{34}S$ values would be expected if sulfur were similarly derived from animal protein. However, no such correlation is present in the Nakum data ($r_s = –0.119$, $p = 0.661$), indicating that sulfur came from a different protein source. Although animal and cereal plant proteins contribute roughly equal amounts of methionine to human tissues (Young and Pellett 1994), lime treatment increases the amount of methionine provided by maize (Katz et al. 1974), thus increasing the amount of maize-derived dietary sulfur in Maya bone collagen. It is, however, important to note that the biologically unavailable sulfur present in the lime used to treat maize itself will not contribute to Maya bone collagen $\delta^{34}S$ values because sulfur must first be assimilated into methionine by plants for it to become bioavailable to humans (Brosnan and Brosnan 2006; see also Rand and Nehlich 2018). Thus, it is possible that nitrogen in human bone collagen from Nakum was derived from the consumption of animals, whereas a significant source of dietary sulfur was methionine derived from lime-treated maize.

5.5.2 Mobility at Prehispanic Nakum

To detect nonlocal individuals isotopically, it is necessary to establish baseline values from the surrounding environment with which human values may be compared. Unfortunately, the $\delta^{18}O$ values of the faunal bone specimens were not analyzed in this study

and thus the faunal baseline consists of a single value of –4.9 ‰ from the enamel of one dog tooth. Studies of modern water in the Maya region provide general spatial distributions of δ^{18}O values (Lachniet and Patterson 2009; Marfia et al. 2004; Wassenaar et al. 2009), although comparison of drinking and body water values requires conversion equations (e.g., Coplen 1988; Iacumin et al. 1996) that may introduce compounding error (Lightfoot and O'Connell 2016; Pollard et al. 2011). Climatic δ^{18}O values have also fluctuated over time (e.g., Medina-Elizalde et al. 2010), and individuals may have used different water sources at a given site (Scherer et al. 2015). The local δ^{18}O range of–5.5 to –2.3 ‰ for Nakum developed from the human bone and enamel samples is, however, consistent with the general trends observed from modern water samples (Lachniet and Patterson 2009; Marfia et al. 2004; Wassenaar et al. 2009) and the δ^{18}O values from other Maya sites in the Southern Lowlands, which typically range from –5 to 0 ‰ (Price et al. 2010).

The δ^{18}O values of two Nakum samples fell well below the local range for the site, suggesting that these individuals lived elsewhere when their tooth enamel and bone formed. The first came from an isolated deciduous second mandibular molar (4508) recovered from an Early Classic context in the core of Str. G. The enamel of this tooth forms in utero (Nelson and Ash 2010), and therefore the nonlocal δ^{18}O value of –6.2 ‰ indicates that the mother of this individual resided in an isotopically distinct region while he/she was *in utero* and may reflect either the movement of this individual, or possibly his/her mother to Peten. The closest known areas with similarly low values are located beyond the Maya lowlands, revealing long distance migration. This sample was recovered from the *talud-tablero* platform of Str. G during the period in which contact between Nakum and Teotihuacan is proposed (Hermes et al. 2006; Koszkul et al. 2006; Źrałka and Koszkul 2007). For many

years, scholars have debated the degree to which *talud-tablero* architecture and other Central Mexican elements represent the actual presence of Teotihuacanos at Maya sites (Braswell 2003). Although individuals with $\delta^{18}O$ values consistent with those from Central Mexico have been identified at other Maya sites, most individuals interred with Teotihuacan-style elements have been identified as local to the Maya region (White et al. 2000, 2001; Wright 2005b; Wright et al. 2010; but see Chinchilla Mazariegos et al. 2015). While the nonlocal $\delta^{18}O$ value of the deciduous molar from Nakum is within the range of values in Central Mexico (Price et al. 2010, 2014; White et al. 2004), it is not possible to exclude other areas, including the Guatemala Highlands and areas outside the Maya region, such as southwestern Mexico and along the Pacific Coast, that also exhibit low $\delta^{18}O$ values (Metcalfe et al. 2009; White et al. 1998). Strontium isotope analysis of this tooth in the future may shed further light on the origins of this individual's mother.

A second low $\delta^{18}O$ value (–8.7 ‰) came from an adult ulna/radius (4500) recovered from a possible termination event at the summit of Str. 99 dating to the Terminal Classic period (Źrałka et al. 2014). Because bone turns over during life, this indicates this person did not live at Nakum long enough for his/her bone collagen to turn over and equilibrate with local bioavailable $\delta^{18}O$ values. As with the tooth sample, it is not possible to identify an exact place of origin, although the low value is consistent with areas in central and southwestern Mexico, the Guatemala Highlands and along the Pacific Coast (Metcalfe et al. 2009; Price et al. 2010, 2014; White et al. 1998, 2004). At Xunantunich, Belize, a nonlocal individual recovered from a Late Classic termination event was interpreted as representing a severing of ties between that site and the place where the individual originated in Central Peten as part of broader political changes in the region (Freiwald et

al. 2014; see also Pagliaro et al. 2003). Incorporating the remains of an individual with a nonlocal $\delta^{18}O$ value in Str. 99 may similarly represent the disassociation of Nakum with that individual's place of origin when the site's power grew following the decline of major centers such as Tikal during the Terminal Classic period (Źrałka and Hermes 2012). Unfortunately, the $\delta^{34}S$ value from this individual cannot corroborate a nonlocal origin, as it may be derived from the limestone-rich soils throughout much of the Maya lowlands or from soils influenced by the sea spray effect. Future stable sulfur isotope analysis of archaeological bone from coastal sites and those in the Guatemalan Highlands is necessary to fully understand the range of $\delta^{34}S$ values present throughout the Maya region.

As with the $\delta^{18}O$ values, the local $^{87}Sr/^{86}Sr$ faunal baseline for Nakum is limited to a single dog tooth (0.7079). Therefore, the $^{87}Sr/^{86}Sr$ values of dentine from the dog tooth and those of three humans were also analyzed as proxies for local soluble strontium in the burial environment (Montgomery et al. 2007) under the premise they were influenced by diagenetic uptake of soil-derived strontium (Budd et al. 2000). The homogenous dentine $^{87}Sr/^{86}Sr$ values (0.7081 ± 0.00003) are consistent with those of modern limestone, water, and plant samples collected from nearby Tikal (0.7078 to 0.7081; Hodell et al. 2004). The human enamel $^{87}Sr/^{86}Sr$ values were slightly higher and more variable (0.7084 ± 0.0002) than the dentine values, although this was not statistically significant ($U = 1.0$, $p = 0.121$), suggesting the enamel values were derived from local dietary strontium sources near Nakum. A local origin is also supported by the $\delta^{18}O_{en}$ values from these same teeth (Fig. 5.7).

Although all enamel values fell within the local $^{87}Sr/^{86}Sr$ range (0.7081 ± 0.00019) proposed for nearby Tikal (Wright 2005a; Fig. 5.7), the Tikal range was based on a very

large sample size and the elevated $^{87}Sr/^{86}Sr$ values in human enamel relative to those expected near the site may be due to numerous factors, including the dietary catchment area and cultural practices (e.g., the consumption of imported salt; Fenner and Wright 2014; Wright 2005a; but see Freiwald et al. 2019). The Nakum Maya enamel $^{87}Sr/^{86}Sr$ values are also similar to those from other sites in the eastern Peten, such as Holmul, Ucanal, and possibly Naranjo (Cormier 2018; Davies 2012; Flynn-Arajdal et al. 2019; Freiwald et al. 2014), which generally are higher than predicted by local baseline samples (e.g., Hodell et al. 2004; also see Wright 2005a). These values are also more similar to those identified in the Belize River Valley and parts of the Yucatan Peninsula than to those in the Peten Lakes district, where lower human and faunal values (which were identical) are found (Freiwald 2020). Therefore, while all three individuals sampled from Nakum obtained their dietary strontium from a similar source local to Nakum when their teeth formed, probably lime-processed maize, future studies should sample a larger number of burials and baseline data to assess this interpretation.

While $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values in tooth enamel reflect drinking water and dietary catchments, respectively, during childhood, $\delta^{34}S$ values in bone collagen offer the opportunity to assess movement later in life. Using archaeological faunal remains, which are less likely to be influenced by pollutant sulfur since the industrial revolution (Richards et al. 2001; Trust and Fry 1992), the local range of environmental $\delta^{34}S$ values (excluding the nonlocal fauna specimen 4325) for Nakum ranges from +12.2 to +15.0 ‰. The human $\delta^{34}S$ values fell within this range, showing that all humans sampled in this study obtained their protein from Nakum or an area with a similar underlying geology in the years prior to their deaths, and is consistent with previous literature that argues most dietary resources

were locally obtained by the Maya (e.g., Emery et al. 2013; Götz 2008; but see Yaeger and Freiwald 2009; Thornton 2011).

However, this isotopically "local" area could be large, given that much of the Yucatan Peninsula is underlain by limestone that exhibits similar $\delta^{34}S$ values. To understand variability in $\delta^{34}S$ values in the Maya region, the Nakum values were compared with those of human bone from Cahal Pech (Awe et al. 2017; Green 2016) and Caledonia (Rand and Grimes 2017), both situated on the Macal River in Belize (see Fig. 5.1). The average $\delta^{34}S$ values from Cahal Pech (+10.9 ± 2.3 ‰, n = 5) and Caledonia (+11.0 ± 2.0 ‰, n = 18) had much larger standard deviations than that of the Nakum human samples (+13.1 ± 0.2 ‰, n = 5). As at Nakum, most sampled individuals from Caledonia and Cahal Pech derived their protein from an area with ^{34}S-enriched soils, which is expected, given that all three sites are situated on limestone. However, some individuals at Cahal Pech and Caledonia had much lower $\delta^{34}S$ values, which may be due to their proximity to the Macal River, which originates in the sulfur-poor Maya Mountains that are expected to exhibit relatively low environmental $\delta^{34}S$ values (Rand and Grimes 2017). It is therefore possible that the individuals from Cahal Pech and Caledonia with low $\delta^{34}S$ values were locals who consumed either terrestrial protein brought to their respective sites from the Maya Mountains or locally available freshwater species influenced by ^{34}S-depleted sulfate carried downstream. Alternatively, it is possible that these individuals originated in the Maya Mountains and moved to these sites later in life, although the $^{87}Sr/^{86}Sr$ values from four of the Cahal Pech individuals indicate they were local to the area (Green 2016). A larger sample size and faunal $\delta^{34}S$ baseline values from Caledonia and Cahal Pech, in addition to

strontium isotope analysis of the Caledonia dentition, would help to improve these preliminary observations.

Finally, a metapodial (4325) consistent with that from a white-tailed deer (i.e., cf. *Odocoileus virginianus*) recovered from a Late Classic context at Nakum exhibited a $\delta^{34}S$ value of +5.0 ‰, much lower than all other values from the site. Because the Maya are known to have traded animal resources over varying distances (Emery 2004a; Götz 2008; Götz and Emery 2013; Sharpe and Emery 2015; Sharpe et al. 2018; Thornton 2011; Yaeger and Freiwald 2009), this outlier may have been imported to the site from a region with ^{34}S-depleted soils, such as the Maya Mountains or the Guatemalan Highlands. Individuals at Nakum had access to resources from the Maya Mountains via trade along the Belize and Holmul Rivers and it is possible this specimen was obtained from this region. If from the Maya Mountains, this non-local deer recovered from Nakum corroborates archaeological evidence that individuals from Nakum utilized trade routes along the Holmul River prior to gaining direct control over these routes during the Terminal Classic following the decline of Tikal and Naranjo (Koszkul et al. 2009). The presence of nonlocal faunal also indirectly implies mobility of either harvesters or intermediary traders that would have to have moved to facilitate the transport of animals throughout the Maya region.

5.6 Chapter 5 Summary and Conclusions

This study presents a multi-isotopic approach to the interpretation of diet and mobility at the prehispanic Maya centre of Nakum. The $\delta^{13}C$ and $\delta^{15}N$ values indicate that the Nakum Maya consumed a maize-based diet supplemented with other plants as well as animals that consumed a C_3-based diet. Although the isotopic values of some individuals

suggest they consumed more maize or maize-fed animals than others, the sample size was too small to evaluate sociocultural differences based on age, sex, social status, or time period. While most Nakum humans and animals exhibited local $\delta^{18}O$, $^{87}Sr/^{86}Sr$, and $\delta^{34}S$ values, it was possible to identify three outliers. Specifically, one individual included in a Late Classic termination ritual and the mother of an individual whose isolated deciduous molar was recovered from an Early Classic context at Nakum were identified as having come to the site from outside the Maya region, possibly from central or southwestern Mexico, the Guatemalan Highlands or the Pacific coast. Finally, the low $\delta^{34}S$ value from a possible white-tailed deer suggests that it was imported to the site from either a volcanic region such as the Guatemalan highlands or, more likely, from the sulfur-poor Maya Mountains.

Finally, this study demonstrates how the analysis of stable sulfur isotope ratios in conjunction with other isotopic assays offers a more nuanced interpretation of protein routing in Maya bone collagen and provides the first faunal baseline $\delta^{34}S$ values in Mesoamerica. Importantly, sampling faunal $\delta^{34}S$ values at Nakum revealed much higher values in the underlying limestone of the Maya region than those at inland sites elsewhere in the world and demonstrates the necessity of obtaining local isotopic baseline data prior to the interpretation of human values.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Isotopic analyses have greatly contributed to the interpretation of Maya subsistence practices and migration during the prehispanic and Colonial periods. Stable carbon ($\delta^{13}C$) and nitrogen isotope ($\delta^{15}N$) analyses have revealed Maya consumption of maize and animal protein (Somerville et al. 2013; Tykot 2002), while strontium ($^{87}Sr/^{86}Sr$) and stable oxygen isotope ($\delta^{18}O$) analyses have successfully been used to investigated migration and trade within and beyond the Maya region (Freiwald et al. 2014; Price et al. 2008; Scherer et al. 2015; Thornton 2011; Wright 2012). Stable sulfur isotope ($\delta^{34}S$) analysis is a novel yet complementary technique for differentiating among sources of dietary protein and identifying nonlocal individuals in archaeological contexts (Nehlich 2015) that has recently been applied in the Maya region (Awe et al. 2017; Green 2006; Rand and Grimes 2017).

Building upon these pioneering studies and the rich archaeological and isotopic databases from the Maya region, the objective of this study was to establish the utility of stable sulfur isotope analysis for understanding prehispanic and Colonial Maya migration and subsistence practices. The research goals were to:

(1) Characterize the variability of environmentally bioavailable $\delta^{34}S$ values throughout the Maya region by establishing a baseline from the values of archaeological fauna.

(2) Test this faunal baseline through the analysis of archaeological human remains from various sites throughout the Maya region.

(3) Demonstrate the contributions and limitations of stable sulfur isotope analysis for the interpretation of Maya migration and subsistence practices.

As this dissertation was written in a "Manuscript Style", the chapters have been prepared separately for publication in various peer-reviewed outlets, but each contributes to a cohesive dissertation.

The theoretical framework necessary for the interpretation of migration and isotopic data in archaeological contexts generally, and in the Maya region specifically, is presented in Chapter 2. Although the conceptualization of migration has fluctuated in conjunction with predominant theoretical paradigms within archaeology and bioarchaeology (Adams et al. 1978; Agarwal and Glencross 2011; Washburn 1951; Zuckerman and Armelagos 2011), advances in method and theory have contributed to a reconceptualization of migration as an important sociocultural process in past societies (Anthony 1990, 1992; Burmeister 2000; Hakenbeck 2008; Scharlotta et al. 2018). Although every method is associated with assumptions and limitations, isotopic techniques have been particularly useful for directly identifying migration to archaeological sites (Hakenbeck 2008; Scharlotta et al. 2018). A minimum definition of isotopically identifiable migration that recognizes both the strengths and limitations of this technique is proposed as *the relocation of a sampled individual to an isotopically distinct environment at least once during his or her life* (Chapter 2:44). Importantly, although isotopic techniques are useful for reconstructing the life histories and identities of individuals, broader aspects of the migration process, including permanency, directionality, temporality, spatial extent, social composition, and scale, may be elucidated

in archaeological contexts when isotopic results are contextualized using multiple lines of evidence.

The identification of migration using stable sulfur isotope analysis is, however, dependent upon variation in environmental $\delta^{34}S$ values throughout an area. This is because the $\delta^{34}S$ values of human and animal bone collagen come from dietary protein (Brosnan and Brosnan 2006; Ingenbleek 2006), which are ultimately derived from environmental sulfate assimilated into amino acids by plants at the base of the food chain (Krouse et al. 1991; Trust and Fry 1992). Based on $\delta^{34}S$ values from similar environments elsewhere in the world, those of the Maya region appear to be sufficiently divergent to identify individuals who migrated among isotopically distinct areas (Rand and Grimes 2017). Indeed, the $\delta^{34}S$ values of 148 archaeological fauna specimens from 13 Maya sites presented in Chapter 3 generally confirm this model, although several results were unexpected (Rand et al. 2021a).

While terrestrial animals in coastal areas had elevated $\delta^{34}S$ values due to the influence of sea spray, marine animals had lower values than predicted, likely due to the influence of microbic dissimilatory sulfate reduction (DSR) in anerobic coastal sediments (Jørgensen et al. 2019) and the input of freshwater from estuarian regions. The $\delta^{34}S$ values of freshwater animals were variable, as expected due to the multiple sulfur inputs along watersheds. However, they were also lower than those of terrestrial animals from the same sites, the elevated $\delta^{34}S$ values of a turtle from Nakum, and the limpkins from Vista Alegre. There also exists variability between terrestrial faunal $\delta^{34}S$ values based on the age of the underlying limestone, wherein animals from areas underlain by older Mesozoic limestone had elevated values compared to those from Paleogene/Neogene regions. These results

indicate that the $\delta^{34}S$ values of terrestrial animals are primarily influenced by the underlying geology, and atmospheric sulfate deposition appears to have a minimal impact on inland $\delta^{34}S$ values. Fauna from inland areas underlain by limestone had elevated $\delta^{34}S$ values that varied based on the age of the lithology, and additional research that builds upon this study of sulfur isotope values throughout the Maya lowlands will verify additional variation proposed herein, such as lower expected $\delta^{34}S$ values of fauna from the Maya Mountains. The elevated $\delta^{34}S$ values of terrestrial animals from inland Maya sites also question the proposition that $\delta^{34}S$ values in excess of +14‰ represent nonlocal individuals from the coast (Madgwick et al. 2019a; Richards et al. 2001) in areas underlain by marine evaporates, such as the Maya region. Local $\delta^{34}S$ values based on archaeological fauna from a variety of catchments are therefore critical for characterizing local variation in environmental $\delta^{34}S$ values, although they may not be appropriate for identifying nonlocal humans, due to variable Maya subsistence practices (e.g., location of agricultural fields in distinct geological zones, nixtamalization, etc.) and because the degree to which sulfur isotopes fractionate at each trophic level may be larger than originally proposed (Webb et al. 2017; but see Krajcarz et al. 2019).

Sulfur isotope analysis provided additional insights into the exchange of animals through the identification of nonlocal fauna. Animals with low $\delta^{34}S$ values were likely obtained from the Mountain Pine Ridge region of the Maya Mountains, which supports previous propositions for specialized hunting of wild game in this region (McAnany 1989; Yaeger and Freiwald 2009). While most animals with nonlocal $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values are large game species or domesticates (Sharpe et al. 2018; Thornton 2011; Yaeger and Freiwald 2009), the presence of a nonlocal agouti and armadillo indicate caution is

necessary when assuming that small mammals with narrow home ranges will represent local isotopic baselines (Price et al. 2002), especially when samples sizes are small. Regardless, the ability of sulfur isotope data to differentiate among sources of dietary protein and to identify nonlocal individuals among the faunal specimens not only provides evidence for Maya trade and interaction, but also demonstrates the potential for this technique to identify migration and subsistence strategies among the Maya themselves.

The faunal sulfur baseline developed in Chapter 3 provided a foundation for the interpretation of the δ^{34}S values of 49 humans from seven Maya sites in Chapter 4. The spatial distribution of the human δ^{34}S values differed from those of terrestrial animals at inland sites, indicating social and economic influences on Maya consumption of protein from multiple, isotopically distinct subsistence catchments. For example, lower human δ^{34}S values at Caledonia and Pacbitun may be influenced by the consumption of protein from the granitic Mountain Pine Ridge of the Maya Mountains or the consumption of freshwater animals. Colonialism also profoundly impacted Maya subsistence practices, as the Colonial period individuals from Mission San Bernabé in Guatemala had much more elevated and homogenous δ^{34}S values than individuals from earlier periods included in this study. A comparison with Contact period individuals from several sites in Belize and Mexico also suggests dietary shifts became more pronounced over time and the degree to which the Spanish presence influenced Maya diets offers an important avenue for future study.

Although sulfur isotope analysis provided interesting insights into prehispanic and Colonial period subsistence practices, this study identified several factors that complicate dietary interpretations of δ^{34}S values from human bone collagen. First, the analysis of both humans and fauna in this study demonstrate that δ^{34}S values vary depending on the type

and age of the underlying limestone and distance from the coast. Various human subsistence practices, such as the consumption of freshwater fish or the location of agricultural fields and hunting regions in distinct sulfur isotope zones may also impact human $\delta^{34}S$ values, as will the individual diets of the consumed organisms. The impact of trophic level fractionation and food processing techniques such as nixtamalization on human bone collagen $\delta^{34}S$ values also require further study.

Despite these interpretive challenges, this study successfully used stable sulfur isotope analysis to identify human migration to Maya sites. While the small sample of isotopically identified nonlocal individuals precluded assessing the migration process, the analysis of additional individuals from multiple Maya sites will provide the basis upon which the theoretical concepts explore in Chapter 2 may be applied in future studies.

Interestingly, sulfur isotope analysis identified migration at a much lower frequency than has been identified using strontium and stable oxygen isotope analyses (Freiwald 2011a; Freiwald et al. 2014; Price et al. 2018a). However, these isotope systems represent different periods of life; the $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values of enamel were formed during childhood and this tissue does not remodel (Moradian-Oldak 2009), whereas bone collagen $\delta^{34}S$ values reflect dietary averages from adolescence to the end of life, depending on the sampled bone and individual physiology in turnover rates (Hedges et al. 2007; Matsubayashi and Tayasu 2019; Parfitt 2001). Thus, the discrepancy in the frequency of identified migrants may be because individuals moved more often early in life. Alternatively, individuals may have been migrants but lived in the region long enough for their bone $\delta^{34}S$ values to equilibrate with those of the local environment. Finally, if large areas have overlapping $\delta^{34}S$ values (i.e., equifinality), this technique alone is insufficient to

characterize the degree of migration throughout the Maya region. It is therefore necessary to analyze multiple isotopes from varying tissues to properly characterize the frequency of migration in past populations, including the Maya.

A multi-isotopic approach not only offers the opportunity to conduct multivariate statistical analyses but also provides insight into the length of time individuals stayed where they were buried and in turn how they were integrated into receiving communities. As has been previously proposed, an individual's nonlocal origin was an important determinant for his or her inclusion in non-funerary ritual contexts at Maya sites (Freiwald et al. 2014:129; Olsen et al. 2014). In this study, the nonlocal individuals from desecratory termination deposits at Xunantunich and Nakum and a dedication deposit at Pacbitun were recent arrivals (either voluntary or involuntary) to these sites and were perhaps included in these rituals to represent a change in the relationship between their place of origin and where they were buried. Conversely, the inclusion of nonlocal individuals in formal funerary contexts within both ceremonial and residential architecture along with local ancestors speaks to their integration into the receiving community, regardless of how long they had lived at their place of burial.

The insights developed in Chapters 2, 3, and 4, were integrated into a multi-isotopic biocultural case study of Maya subsistence practices and migration at prehispanic Nakum, Guatemala. The bone collagen $\delta^{34}S$, $\delta^{13}C$, and $\delta^{15}N$ values of 16 archaeological fauna provided a baseline with which the values of five humans were compared. Of these animals, a turtle had an unexpectedly elevated $\delta^{34}S$ value for freshwater animals that was indistinguishable from the terrestrial animals, and one deer had a much lower $\delta^{34}S$ value indicating it was traded to the site, perhaps from the Mountain Pine Ridge area of Belize.

Although the human $\delta^{13}C$ and $\delta^{15}N$ values were variable, their $\delta^{34}S$ values were quite homogenous and indistinguishable from those of the animals from the site, indicating the consumption of local protein. Although the strontium isotope values were similarly interpreted as local, the analysis of bone $\delta^{18}O$ values found an individual from a Terminal Classic termination ritual mentioned above was a recent migrant to the site. The $\delta^{18}O$ value of a deciduous molar from a Central Mexican context at Nakum was consistent with values from Teotihuacan (Price et al. 2010, 2014), but other regions cannot be ruled out due to equifinality. This case study illustrates that a multi-isotopic biocultural approach that considers the archaeological context can circumvent the issue of equifinality and provide important insights into subsistence strategies, migration, and interregional interaction and relations in the Maya region.

6.1 Recommendations for Future Research

Because sulfur isotope analysis is a relatively new technique in archaeological studies, there are multiple opportunities for future research. These include methodological research in both the Maya region and in the archaeological application of stable sulfur isotope analysis more generally. Beyond methodology, archaeological isotope studies would also benefit from greater engagement with theoretical conceptualizations of migration in past and present societies.

This dissertation research has demonstrated how stable sulfur isotope analysis can provide important insights into prehispanic Maya subsistence strategies and migration, although the sample size was limited. The analysis of stable sulfur isotope analysis of additional human and faunal remains from Maya archaeological contexts will expand upon

this dissertation research and better characterize the variation of $\delta^{34}S$ values over time and space. For example, the faunal samples included in this study were predominantly from terrestrial animals, and additional analysis of freshwater and, particularly, marine species will provide greater insights into Maya use of diverse resource catchments. Similarly, the analysis of samples from underrepresented regions with diverse geologies, including the Northern Lowlands, Maya Mountains, Motagua Valley, Highlands, and Pacific coast will better characterize the variability of $\delta^{34}S$ values throughout the Maya region, providing additional insights into long distance trade and migration. Furthermore, most human and faunal samples included here date to the Late Classic period, and the sulfur isotope analysis of human and faunal remains from multiple periods will clarify how subsistence practices and migration varied over time.

More generally, the archaeological application of stable sulfur isotope analysis would benefit from better understandings of sulfur in the biosphere, as well as the comparability of results from different studies. For example, although the difference between the $\delta^{34}S$ values of consumers and their diets ($\Delta^{34}S_{tissue\text{-}diet}$) were initially assumed to be negligible (Peterson and Fry 1987), the fractionation associated with higher trophic levels is now known to be variable, depending on the sampled tissue, species, metabolic processes of individual consumers, and the amount of protein in the diet (McCutchan et al. 2003; Richards et al. 2003; Tanz and Schmidt 2010). Dietary studies specifically designed to identify the offset between the $\delta^{34}S$ values of the bone collagen from large mammals and their diets, as has recently been explored by Webb and colleagues (2017), will contribute to refined interpretations of human subsistence practices in archaeological contexts, including those in the Maya region.

It is also necessary to establish the amount of sulfur derived from different sources of dietary protein. For example, although animal and cereal plant proteins contribute nearly equal amounts to dietary protein (Young and Pellet 1994), lime treatment (i.e., nixtamalization) increases the amount of methionine available from maize (Ellwood et al. 2013; Katz et al. 1974). Therefore, the $\delta^{34}S$ of Maya bone collagen may preferentially reflect the consumption of maize rather than animal protein, complicating the interpretation of human diet and migration through comparison with baselines developed from faunal $\delta^{34}S$ values.

Establishing the comparability of $\delta^{34}S$ values generated by different laboratories is also necessary. Pestle and colleagues (2014) found interlaboratory $\delta^{13}C$ and $\delta^{15}N$ values to be generally comparable, but that there were significant differences in $\delta^{18}O$ values analyzed by different laboratories. An interlaboratory comparison of $\delta^{34}S$ values has not yet been published; however, the preliminary results presented in Appendix B indicate that laboratories that analyze similar amounts of collagen combined with the same catalyst reactant (e.g., V_2O_5) prior to combustion produced comparable $\delta^{34}S$ values. However, additional work is needed, as the data generated from laboratories that analyze larger amounts of sample combined with different catalysts (e.g., sucrose) may produce incomparable values. It is therefore important to establish the interlaboratory comparability of $\delta^{34}S$ values, especially given recent interest in large-scale meta-analyses of archaeological culture areas that compile data from multiple isotopic studies (Szpak et al. 2017a) that can be facilitated through large, publicly available online databases, such as IsoArcH (https://isoarch.eu/).

Multi-isotopic approaches to migration that incorporate sulfur isotope analyses are another fruitful avenue for future research. For example, although the principle of equifinality precludes the proveniencing of nonlocal individuals, the integration of multiple isotopic analyses can narrow down potential areas of origin (Freiwald 2011a; Laffoon 2013:420). The multi-isotopic analyses of multiple tissues from the same individual that form at different periods (e.g., enamel and bone collagen) also allows more detailed reconstructions of migration across the lifetime of an individual (Rand et al. 2021b). Finally, a multi-isotopic approach offers the opportunity to employ multivariate statistical techniques to develop quantitative isoscapes of the Maya region, as has recently been done for western Europe (Bataille et al. 2021).

While isotopic techniques are invaluable tools in archaeology because they provide direct evidence for migration that is otherwise elusive in other data sets (Hakenbeck 2008; Knudson 2011:232), researchers must be aware of the limitations associated with these techniques and avoid uncritically applying terminology in studies of the past (Scharlotta et al. 2018). Archaeological isotope studies also need to move beyond simply identifying nonlocal individuals to actively engaging with theoretical perspectives to reconstruct the sociocultural processes of past migrations. The incorporation of the diaspora framework into isotopic studies of past migrations (Baltus and Baires 2020; Eckardt and Müldner 2016; Emerson et al. 2020), is one such example, although this may not be applicable in all contexts, such as in the Maya region.

Such interdisciplinary approaches can provide insights into various aspects of migration in the past, such as their permanency, directionality, temporality, spatial extent, social composition, and scale. For example, ceramic sequences and radiometric dating of

multiple nonlocal individuals will help to reconstruct how migration streams from certain areas fluctuated over time in conjunction with changing sociopolitical conditions, thus providing important insights into interregional interaction over time. Although the small sample of nonlocal individuals precluded assessing migration processes in this study, a multi-isotopic approach that considered the archaeological and historical contexts of the individuals and sites elucidated the length of time individuals lived at the site where they were buried and the degree to which nonlocal individuals were integrated into receiving communities. Thus, a greater engagement with archaeological conceptualizations of the process of migration in the past will enhance the interpretive potential of isotopic techniques, especially when incorporated into future interdisciplinary studies.

In conclusion, this doctoral research demonstrates that the analysis of stable sulfur isotopes from archaeological human and faunal bone collagen contributes meaningful insights into Maya subsistence practices and migration. Building upon pioneering studies of sulfur isotope analyses in this culture region (Awe et al. 2017; Green 2016; Rand and Grimes 2017), the faunal baseline confirms that there exists sufficient variation in bioavailable $\delta^{34}S$ values throughout the Maya region to identify subsistence strategies and migration in this culture area. The identification of animals with nonlocal $\delta^{34}S$ values also provides insight into Maya resource procurement and animal trade. A comparison of the human $\delta^{34}S$ values with faunal baselines allows more detailed understandings of Maya utilization of multiple resource catchments, as does the interpretation of $\delta^{13}C$ and $\delta^{15}N$ values from the same individuals. Nonlocal individuals that moved later in life were identifiable as those with distinct bone collagen $\delta^{34}S$ values, and the combination of $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values from enamel representing childhood residence with the $\delta^{18}O$ and

$\delta^{34}S$ values from bone hydroxyapatite (bioapatite) and collagen, respectively, also allowed the length of time a nonlocal individual resided in an area prior to death to be explored, providing insights into interregional interaction and how migrants were integrated into receiving communities. Thus, this dissertation has established that stable sulfur isotope analysis offers a robust yet complementary tool for archaeological investigations of Maya subsistence practices, animal exchange, and migration.

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APPENDIX A

DETAILED METHODOLOGY

A.1 Introduction

Numerous researchers and projects generously provided human and faunal bone samples for this study. The projects during which the materials were excavated are described in more detail in section A.2. In most cases, the human and faunal remains have been previously analysed by project osteologists and zooarchaeologists, respectively, and these researchers and studies are cited in Section A.2. The Nakum faunal collection had not yet been subjected to zooarchaeological analysis, and so its analysis by the author is described in more detail in Section A.3. The methods used to clean, prepare, and analyze human and faunal bone collagen samples are described in Section A.4.1. The preparation and analysis of the stable carbon and oxygen isotopes of bone and tooth enamel bioapatite and strontium isotopes from tooth enamel and dentine from the Nakum samples (Chapter 5) are described in Sections A.4.2 and A.4.3, respectively. The method used to calculate analytical uncertainty is described in Section A.5, and the detection of samples that were diagentically altered is discussed in section A.6. Finally, the methods used to calculate local baseline ranges are reviewed in section A.7, and the statistical techniques employed in this dissertation are described in section A.8.

A.2 Sample Acquisition and Previous Analyses

Caledonia, Cayo District, Belize, was excavated by the Trent-Cayo Archaeological Project directed by Dr. Paul Healy (Trent University) and by Dr. Jaime Awe (Northern Arizona University) as part of his MA research under the supervision of Dr. Healy (Awe 1985). Dr. Herman Helmuth (Trent University) performed the osteological analyses of the human remains from Caledonia (Awe 1985; Healy et al. 1998), and the author analyzed the

stable carbon, nitrogen, and oxygen isotopes of these remains as part of her MA research (Rand 2012, 2017; Rand et al. 2015b). Dr. Healy granted permission for the Caledonia human remains to be reanalyzed in this study.

The human and faunal remains from Pacbitun, Belize, were excavated during Trent University's Pacbitun Archaeological Project directed by Dr. Healy (Campbell-Trithart 1990; Sunahara 1995). Osteological analyses were performed by Dr. Helmuth, and these data were compiled by Robertson (2011). Zooarchaeological analysis were conducted by Dr. Kitty Emery (Florida State Museum, University of Florida) and Polydora Baker (Historic England; Baker 1988; Emery 1987; Emery and Baker 2014). Carbon and nitrogen isotope analyses of the human remains have been previously conducted (Coyston 1999; White et al. 1993), and Dr. Healy granted permission for their reanalysis.

The midden from Moho Cay, Belize, was excavated by the Moho Cay Archaeological Project under the direction of Dr. Healy as part of Dr. Heather McKillop's (Louisiana State University) Master's research (Healy and McKillop 1980; McKillop 1980, 1984). Dr. McKillop conducted the zooarchaeological analysis (McKillop 1984) and Dr. Healy granted permission for isotopic analyses.

The faunal material from Laguna de On Shore and Island, Caye Coco, Caye Muerto, and Chanlacan in Belize were recovered as part of Dr. Marilyn Masson's (University at Albany, State University of New York) doctoral research (Masson 1993) and her subsequent Belize Postclassic Project excavations (Delu et al. 2002; Ferguson et al. 2003; Masson and Rosenswig 1997, 1998, 1999; Rosenswig and Masson 2000, 2001). Dr. Masson conducted the zooarchaeological analysis (Masson 1993, 1999, 2004) and granted permission for the isotopic analysis of these specimens.

The two faunal specimens from Caracol, Belize, were excavated by the Tourism Development Project under the direction of Dr. Awe, and Dr. Freiwald performed the species identifications. Permission to export the samples for isotopic analysis was granted by the Belize Institute of Archaeology (IOA) to Dr. Awe, who provided the samples for this project.

The human and faunal remains from Xunantunich and San Lorenzo in Belize were excavated by several projects, and Drs. Jason Yaeger and M. Kathryn Brown (The University of Texas at San Antonio) granted permission for their analysis. Specifically, the samples were recovered during a rescue excavation by Drs. David Pendergast (Royal Ontario Museum) and Elizabeth Graham (University Collagen London) (Pendergast and Graham 1981), the Xunantunich Archaeological Project (XAP) led by Drs. Richard Leventhal (University of Pennsylvania) and Wendy Ashmore (University of California, Riverside), the Xunantunich Settlement Survey (XSS) led by Dr. Ashmore (Leventhal et al. 2010), the Tourism Development Project (TDP) directed by Drs. Awe and Allan Moore (IOA; Audet 2006; Yaeger 2005), and the Mopan Valley Preclassic Project (MVPP) under the direction of Dr. Brown (Brown 2013; Sword 2014). San Lorenzo was excavated from 1991 to 1996 by XAP and for Dr. Yaeger's doctoral research (Chase 1992; Yaeger 2000; Yaeger and Villamil 1996). Dr. Bradley Adams (New York University Langone Health) performed the osteological analysis of the human remains excavated by XAP (Adams 1998; Yaeger 2000), and Dr. Freiwald is currently conducting the osteological analysis of the human skeletons excavated by the more recent projects (personal communication, 2018). Dr. Freiwald also conducted the zooarchaeological analysis and the isotopic analysis of the human and faunal remains from Xunantunich and San Lorenzo (Freiwald 2010, 2011a,

2011b; Freiwald et al. 2014; Yaeger and Freiwald 2009). Permission to export the samples for analysis was granted by the Belize Institute of Archaeology (IOA).

The faunal specimens from Vista Alegre were excavated by the Proyecto Costa Escondida under the direction of Dr. Jeffrey Glover (Georgia State University; Glover and Rissolo 2013; Glover et al. 2013; Rissolo and Glover 2006). Zooarchaeological analyses were conducted by Elizabeth Ojeda Rodriguez (Universidad de Granada), and Dr. Glover provided the samples for this study. The Instituto Nacional de Antropología e Historia (INAH) of Mexico granted permission for the author to export these samples to Canada for isotopic analysis.

The faunal remains from Oxtankah, Ichpaatun, and San Miguelito, in Mexico were provided by Dr. Allan Ortega Muñoz (INAH) and were excavated by the Proyecto Arqueológico Oxtankah (de Vega Nova et al. 2013). Dr. Ortega-Muñoz conducted zooarchaeological analyses (Ortega-Muñoz et al. 2014) and provided the samples for analysis. The author was granted permission by the INAH to export the samples for isotopic analysis.

The human materials from Chac, Mexico, were excavated as part of the Early Puuc Urbanism at Chac II archaeological project directed by Dr. Michael Smyth (Rollins College; Smyth et al. 1998). Those from Calakmul were excavated by the Proyecto Arqueológico Calakmul under the direction of Ramón Carrasco Vargas (Instituto Nacional de Antropología e Historia; Carrasco Vargas and Colón González 2006). Osteological analyses of the human remains from both sites were conducted by Dr. Vera Tiesler (Universidad Autónoma de Yucatan), and the strontium, carbon, oxygen and nitrogen isotopes of the Calakmul human remains have been previously analyzed (Price et al. 2018a;

Tiesler 1999, 2001). Dr. Tiesler granted permission for the isotopic analyses of these samples.

Finally, the fauna specimens from Tayasal and human samples from Mission San Bernabé, Guatemala, were excavated by the Itza Archaeology project directed by Dr. Timothy Pugh (City University of New York) and Evelyn Chan Nieto (Centro Universitario de Peten; Pugh et al. 2016). Dr. Freiwald conducted the zooarchaeological and isotopic analysis of the faunal remains (Freiwald 2012; Freiwald and Pugh 2018). Dr. Katherine Miller Wolf (University of West Florida) performed the osteological analysis of the human material (Miller 2012), and the strontium and oxygen isotopes from these remains have been previously analyzed (Freiwald et al. 2020). Permission to export these samples for isotopic analysis was granted by the Guatemalan Instituto de Antropología e Historia (IDAEH) to Dr. Pugh, Ms. Chan Nieto, and Dr. Miller Wolf.

A.3 Nakum Faunal Species Identification and Sample Selection

Permission to sample the Nakum faunal remains was granted by Dr. Jarosław Źrałka (Uniwersytetu Jagiellońskiego), although they had not yet been subjected to zooarchaeological analysis. In June 2017, the author conducted preliminary faunal species identifications at the Proyecto Arqueológico Nakum (PAN) Field Laboratory based on visual and descriptive comparisons (Florida Museum of Natural History 2018; France 2009), as a comparative collection was unavailable. Helpful insights and resources were provided by Ms. Ojeda Rodriguez and Deirdre Elliot (Department of Archaeology, Memorial University of Newfoundland). The identification of the *Mazama* sp. calcaneus (4327) was confirmed through a comparison with identified specimens from the Laguna de

On faunal collection provided by Dr. Masson, and the *Canis lupus familiaris* left carnassial from Nakum (4495) was identified through comparison with a specimen available in the Memorial Applied Archaeological Sciences (MAAS) Laboratory. Finally, the identifications the *Trachemys venusta* femur (4318) and a metacarpal (4325) consistent in size and shape to that of *Odocoileus virginianus* were conducted by Arianne Boileau (Department of Anthropology, University of Florida).

The human remains from Nakum were analyzed by the project osteologist Varinia Matute (Źrałka et al. under review). Based on preservation, context, and species identification, 18 faunal bone samples and one faunal tooth were selected by AR for isotopic analysis. Sixteen human bone and tooth samples were selected by Dr. Źrałka based on preservation and the broader research goals of the Proyecto Arqueológico Nakum (PAN).

A.4 Sample Preparation and Analysis

A.4.1 Bone Collagen Preparation and Analysis

Bone and tooth specimens were ultrasonicated in deionized (DI) water (18 MΩ; Zeneer Power I Integrate, Human Corporation®, Republic of Korea) for 5 minutes, the water was decanted and replaced, the specimen was again ultrasonicated, and this process was repeated until no precipitate was observed. The cleaned specimens were then placed in a 40°C oven (VWR Gravity Convection Oven 3.7 CF) to dry overnight. Approximately 1 g of bone was then removed from each specimen using a rotary tool (Jobmate® Model No: 54-4777-0) and the surfaces were cleaned using an air abrasion system (S.S. White Airbrasive® 6500 System, AccuFlo Micro-Abrasive Blaster Simoom Technology®).

Collagen was extracted from the bone samples using a modified version of the Longin (1971) method (Honch et al. 2006; Nehlich and Richards 2009; Rand et al. 2015a) to maximize the quantity and quality of collagen obtained from poorly preserved bone that is typical of tropical environments, including the Maya region. The bone samples were weighed into labelled screw-cap test tubes and demineralized in 0.5 M hydrochloric acid (HCl) for several days at 4°C. The acid was changed every two days until effervescence ceased and demineralization was complete, which took between four and thirty days. Once demineralized, the samples were rinsed three times in deionized water (DI H_2O) to reach a neutral pH. The samples were centrifuged between rinses and the washings were removed using glass Pasteur pipettes to minimize sample loss. To remove carbon-containing humic contaminants that influence the $\delta^{13}C$ and wt %C values, the demineralized samples were submerged in 8 ml of 0.1 M sodium hydroxide (NaOH) for successive 20-minute intervals until a colour change in the solution was no longer apparent (Szpak et al. 2017b). The original samples from Caledonia were not treated with NaOH, but the resulting isotopic values from these and resamples from the same specimens prepared with a NaOH treatment were not statistically different (Appendix B). Following treatment, the samples were thoroughly rinsed by removing the solution using pipettes, adding DI H_2O and centrifuging until a neutral pH of 7 was obtained. The vials were filled with DI H_2O and drops of 0.5 M HCl were added using a pipette until a pH of 3 was obtained before the residues were gelatinized at 70°C by placing the sealed vials in a heating block for 48 hours. This causes the soluble collagen to go into solution, leaving non-collagenous material as a "pellet" in the bottom of the tube.

Next, the samples were centrifuged to thoroughly separate the pellet from solution, the latter of which was pipetted into a test tube and the former was discarded. To remove particulates, the solution was then passed through Ezee-Filter™ particle filters (Elkay Laboratory Products) previously cleaned by ultrasonication in DI H_2O for 20 minutes (Brock et al. 2007, 2013; Wood et al. 2010). The filtered liquid was poured into the sample chamber of a 30 kDA MWCO (30,000 Dalton molecular weight cut off) ultrafilter (Pall Laboratory Microsep™ Advance Centrifugal Filters and Sartorius Vivaspin® Ultrafiltration Concentrators) cleaned by centrifuging three times in DI H_2O for 5 minutes at 2300 rpm, followed by a heated ultrasonic bath (70°C) in DI H_2O for one hour, and centrifuging an additional two times in DI H_2O. This cleaning method is a modified version of that used by the Oxford Radiocarbon Accelerator Unit (Brock et al. 2007; Bronk Ramsey et al. 2000, 2004; Higham et al. 2006; Jacobi et al. 2006) with the additional step of heating the ultrasonic bath (Fülöp et al. 2013; Svyatko et al. 2012). Because the ultrafilter sample chambers only accommodate 6 ml, the first half of the sample was centrifuged in the ultrafilters to separate the degraded short chain amino acids and inorganic sulfur components from the well-preserved collagen (Nehlich et al. 2011:4969). The purified collagen was poured from the ultrafilter sample chamber into a labelled Pyrex test tube, and the process repeated for the second half of the sample. Any material that passed through the ultrafilter was discarded.

The Pyrex test tubes were then covered with parafilm that was punctured to allow for evaporation and then placed in a test tube rack in a –20 °C freezer for 24 hours. The rack was placed at an acute angle so that the liquid froze as a thinly distributed layer along the tube with no more than 10 mm at the thickest part to increase surface area during

lyophilisation. The tubes were then transferred to a glass beaker and placed in a –60 °C ultra-low temperature freezer (VWR) for 24 hours. After freezing, the samples were lyophilized in a –80 °C freeze dryer (Virtis® Benchtop 2K) at < 20 mTorr for 48 hours. The dry samples were then carefully weighed into labelled 2 ml plastic centrifuge tubes to calculate collagen yield.

The stable sulfur isotope ratios and concentrations of the initial samples from Caledonia prepared without a NaOH treatment were analyzed at the Stable Isotope Laboratory of the CREAIT Network's TERRA Facility at Memorial University of Newfoundland (MUN). Samples of collagen weighing approximately 15 mg were weighed into tin capsules with 1 mg vanadium pentoxide (V_2O_5) and combusted in a Carlo Erba NA1500 Series II elemental analyzer (EA) (Thermo Scientific) and channelled to at MAT 252 isotope ratio mass spectrometer (IRMS) (Thermo Scientific) via a ConFlo III interface (Thermo Scientific) for analysis. Analytical uncertainty is presented in Appendix C.

Six of the original Caledonia bone samples prepared without a NaOH treatment and 13 resamples, as well as samples from Pacbitun, Moho Cay, Laguna de On Island and Shore, Caye Coco, Caye Muerto, Chanlacan, Nakum, Vista Alegre, Oxtankah, Ichpaatun, and San Miguelito prepared with a NaOH treatment were sent to the Stable Isotope Laboratory in the Department of Earth and Planetary Sciences at the University of Tennessee Knoxville for stable sulfur isotope analysis. Five milligrams of collagen were weighed into tin capsules with 1 mg V_2O_5 then combusted in an EC S4010 EA (Costech) and analyzed on a Delta V Plus IRMS (Thermo). The analytical uncertainty is presented in Appendix C.

The stable sulfur isotope ratios and concentrations of the samples from San Lorenzo, Xunantunich, San Bernabé, and Calakmul were analyzed by the Ján Veizer Stable Isotope Laboratory, University of Ottawa. Approximately 20 to 50 mg of collagen was mixed with at least twice its weight of sucrose and combusted in an Isotope Cube EA (Elementar) coupled to a Delta Plus XP IRMS (Thermo Scientific) via a ConFlo IV (Thermo Scientific) interface. Due to the large amount of collagen needed for analysis, samples were not analyzed in duplicate. Analytical uncertainty associated with this analysis are presented in Appendix C.

The stable carbon and nitrogen isotope ratios and concentrations of the original Caledonia samples, as well as the samples from Pacbitun, Moho Cay, Laguna de On Island and Shore, Caye Coco, Chanlacan, Caye Muerto, and Nakum were analyzed at MUN. Approximately 1 mg of collagen was weighed into tin capsules and flash combusted in a Carlo Erba NA 1500 Series II EA (Thermo Scientific) and transferred to a Delta V-Plus IRMS (Thermo Scientific) IRMS for analysis via continuous flow (Finnigan™ ConFlo III, Thermo Scientific). Eight of the original samples and eight resamples from Caledonia, as well as samples from Vista Alegre, Oxtankah, Ichpaatun, San Miguelito, San Lorenzo, Xunantunich, San Bernabé, Tayasal, Caracol, Chac II, and Calakmul were sent to the Ján Veizer Stable Isotope Laboratory at the University of Ottawa for stable carbon and nitrogen isotope analysis. Samples of bone collagen weighing approximately 1 mg were measured into tin capsules and combusted in a Vario EL Cube (Elementar, Germany) EA coupled to a Delta Advantage IRMS (Thermo, Germany) via a Conflo III (Thermo, Germany) interface. Ten samples were run in duplicate and analytical uncertainty is presented in Appendix C.

A.4.2 Nakum Bone and Tooth Enamel Bioapatite Preparation and Analysis

The bioapatite of bone (n = 9) and tooth enamel (n = 7) samples from Nakum was prepared for stable carbon and oxygen isotope analysis following established procedures (Garvie-Lok et al. 2004; Koch et al. 1997; Lee-Thorp and van der Merwe 1991). Samples weighing 15 mg were powdered from the cleaned bone and enamel specimens using a microdrill (Gorbet USA Micromotor drill base unit and handle 110/220 V) fitted with diamond tipped burrs. Bone samples were placed in labelled 2 ml microcentrifuges tube and treated with 1.8 ml of bleach (NaOCl, ~1.7% v/v) under constant agitation for 3 hours or until the reaction ceased, whereas enamel samples were left to react under constant agitation for no more than 25 minutes. The samples were centrifuged at 10,500 rpm for 2 minutes, the solution was decanted and replaced with DI H_2O, the samples were centrifuged, and the process repeated for a total of three DI H_2O rinses. The samples were then treated with 1 ml of 0.1 M acetic acid (CH_3COOH) for 8 minutes, before immediately being centrifuged at 10,500 rpm for 2 minutes. The solution was then decanted, and the samples were rinsed by centrifuging in DI H_2O three times before being placed in a freezer overnight and lyophilized in a –80°C freeze dryer (Virtis® Benchtop 2K) at < 20 mTorr for 48 hours.

Two milligrams of prepared bone or tooth enamel bioapatite samples were then weighed into capped glass vials in the SIL at MUN. The vials were placed in a GasBench II (Thermo, Germany) where they were flushed with helium prior to injection with phosphoric acid. The generated CO_2 gas was transferred to a Delta V-Plus IRMS via a Conflo III interface for analysis. Analytical uncertainty is presented in Appendix C.

A.4.3 Strontium Isotope Preparation and Analysis of the Nakum Tooth Samples

Four teeth from Nakum (3 human and 1 dog) were prepared for strontium isotope analysis following standard procedures (Copeland et al. 2008; Madgwick et al. 2017). Samples of enamel and dentine were removed from each tooth using a microdrill with a diamond-tipped bit (Gorbet USA Micromotor drill base unit and handle 110/220V), ultrasonicated in DI H_2O (18.3 MΩ) and rinsed with acetone (C_3H_6O). The dry enamel (20 mg) and dentine (10 mg) samples were weighed into clean 3 ml Savillex™ (Minnetonka, MN, USA) vials and closed-vessel digested in 1.5 ml of 8 M nitric acid (HNO_3) on a hot plate at 100 °C.

Strontium was extracted from the samples via ion-exchange chromatography. First, pre-made 2 ml pipette tip columns containing a polyethylene (PE) frit were cleaned with successive 1 ml rinses of DI H_2O (18.3 MΩ), 6 M HCl, and 8 M HNO_3 before 200 µl of pre-cleaned Eichrom Sr-Spec resin (Lisle, Illinois, USA) was added and successively rinsed three times each with 6 M HCl, DI H_2O, and 8 M HNO_3 (De Muynk et al. 2009; Horwitz et al. 1992). The digested samples were transferred directly onto the resin bed and rinsed three times with 8 M HNO_3 before strontium was eluted from the resin with 2 ml of DI H_2O. The solution was reloaded onto the resin from the original Savillex™ sample vial and the process repeated to maximize strontium recovery before the sample was acidified with 75 µl 8 M HNO_3 to make a 3% solution. All acids (e.g., HCl and HNO_3) in the strontium isotope preparation method were purchased as high purity grade and were single distilled prior to use. Finally, both a procedural standard (NIST SRM 1400, Bone Ash) and a

procedural blank were included in the analysis of each batch of sample column Sr extractions (n = 8).

Samples were analyzed at CREAIT Network's Micro Analysis Facility (MAF) at MUN, where they were diluted in 3 % HNO_3 prior to analysis on a Thermo Scientific Neptune™ multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS). The analytical standard NIST SRM 987 was measured along with the samples, procedural standard, and blank at a ratio of 1:6. The deviation of the average value for SRM 987 during the analytical session from the reported value of 0.710248 (Avanzinelli et al. 2005) was used to correct all sample values, which resulted in an $^{87}Sr/^{86}Sr$ value adjustment to the samples of -0.000031. The long-term average $^{87}Sr/^{86}Sr$ values of SRM 987 is 0.713145 ± 0.000008 (2σ, n = 73) over 50 static cycles of data collection. Finally, the signal intensities of total procedural blanks gave ^{88}Sr = 0.017 V and are considered negligible (<0.1 %) when compared to the typical ^{88}Sr intensities of the samples and standards.

A.5 Analytical Uncertainty

Comprehensive reporting of analytical uncertainty is necessary for comparing isotopic data generated by different laboratories under different conditions, especially given the trend towards meta-analyses of data from specific archaeological regions and time periods (Szpak et al. 2017a). It is, however, important to recognize that different measurements, for example analytical precision and accuracy, do not represent the same aspects of analytical uncertainty (Fig. A.1). When isotopic measurements are tightly clustered, they are precise (i.e., repeatable) but may not necessarily be accurate reflections

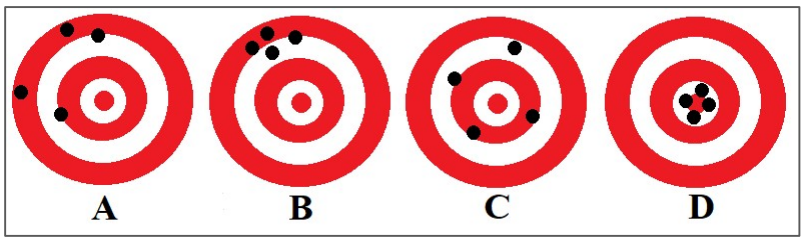

Figure A.1: Accuracy versus precision. (A) No accuracy or precision; (B) Precision but no accuracy; (C) Accuracy but no precision; and (D) Accuracy and precision.

of the 'true' isotopic value of the analyzed material (Fig. A.1.B). Alternatively, measurements may average close to the true value but are widely spaced and are therefore imprecise (Fig. A.1.C). Ideally, measurements should be both accurate and precise (Fig. A.1.D).

Analytical uncertainty was determined separately for each lab and analyses (i.e., carbon and nitrogen versus sulfur isotope analysis) using the method outlined in Szpak et al. (2017a). Three measurements of analytical error, including measurement precision ($u(R_w)$) and accuracy ($u(bias)$), as well as standard uncertainty (u_c), are summarized below and readers are directed to Szpak et al. (2017a:Appendix F) for more detail. These measurements of analytical uncertainty were calculated separately for collagen carbon, nitrogen, and sulfur, and bioapatite oxygen and carbon analyzed at each of the three laboratories utilized in this research (see Sections A.3.1 and A.3.2) using the Microsoft® Excel® spreadsheet provided in Appendix G of Szpak et al. (2017a) and the results are described in detail in Appendix C of this dissertation.

To assess analytical uncertainty, standard reference materials (SRMs) are included in each analytical session (i.e., run). Calibration standards with known δ-values relative to internationally agreed-upon standards are included with samples in each run and are used

to calculate a two-point calibration curve that anchors the raw isotopic values at both the high- and low-ends of the range of δ-values (Coplen et al. 2006; Szpak et al. 2017a).

Internationally agreed-upon isotopic measurement scales include Vienna PeeDee Belemnite (VPDB) for carbon, air N_2 (AIR) for nitrogen, Vienna Cañon Diablo Troilite (VCDT) for sulfur, and Vienna Standard Mean Ocean Water (VSMOW) or VPDB for oxygen (Coplen 1994; Coplen et al. 2006; Coplen and Krouse 1998; Junk and Svec 1958). Because internationally certified SRMs are calibrated to the appropriate isotopic measurement scale and are assigned accepted values, they are preferred for calibration of the isotopic data. In contrast, the isotopic compositions of internal (i.e., in-house) standards represent long-term averages obtained from a specific laboratory that have been calibrated to the internationally agreed upon SRMs. Internal SRMs are more appropriate as check standards and should be matrix-matched, meaning that they are composed of materials that have similar chemical compositions to those of the samples being analyzed (Szpak et al. 2017a).

Analytical precision ($u(R_w)$) reflects the repeatability of measurements and the presence of random error. In isotopic analysis, precision is evaluated using the variation in the measurements of standard reference materials (e.g., calibration or check standards) with or without assigned δ-values as well as repeated measurements of sample aliquots (replicates) from the same analytical session. Analytical precision was calculated from the pooled standard deviation of all repeated measurements during the relevant analytical sessions at each laboratory, including those of check and calibration standards (s_{srm}) and sample replicates (s_{rep}) (Szpak et al. 2017a:Appendix F).

Analytical accuracy (*u(bias)*) refers to measurement bias or systematic errors in measurement and how close a measurement is to the "true" value of the analyte. The accuracy of isotopic measurements can only be evaluated by including check standards in each analytical session that are not used for calibration of the results, because the δ-values of calibration standards are calibrated to known values (Szpak et al. 2017a:611). The degree to which the measured δ-values of the check standards deviate from their known values indicates the degree to which the measured δ-values of the samples deviate from their "true" value. Analytical accuracy therefore represents systematic errors in the measurements caused, for example, by instrumental drift (Szpak et al. 2017a:611). Here, measurement accuracy was calculated by factoring in the long-term uncertainty in the known isotopic measurements of the check standards by calculating the root-mean-square of the difference between their observed mean and known values (Szpak et al. 2017a).

Finally, Szpak et al. (2017a) advise researchers to report the total analytical uncertainty, or standard uncertainty (u_c). This measurement combines the calculations of precision ($u(R_w)$) and accuracy (*u(bias)*) into a more comparable measurement of analytical uncertainty applicable across studies (Szpak et al. 2017a:Appendix F) and this approach was adopted in this research.

A.6 Identifying Diagenesis

Diagenesis is the postmortem alteration of the chemical composition of bones and teeth as a result of the burial environment. Diagenesis is problematic because it causes the isotopic composition of sampled tissues to differ from those obtained during life (i.e., biogenic values). Specifically, unidentified diagenetic effects on isotopic values can have

a profound influence on the interpretation of isotopic results and the resulting archaeological understandings of mobility and diet in the past (Krueger 1991; Lee-Thorp and van der Merwe 1991; Wright and Schwarcz 1996). Thus, it is necessary to minimize the influence of diagenesis using appropriate sample preparation and analytical techniques and to identify and remove diagenetically altered values prior to interpretation. The precautions taken to identify and limit the effects of diagenesis used in this study are described below for bone collagen, bone bioapatite, and tooth enamel bioapatite.

A.6.1 Bone Collagen

The presence of diagenesis in bone collagen samples was assessed using established criteria, including percent by weight of carbon (wt. %C), nitrogen (wt. %N), and sulfur (wt. %S), as well as the atomic carbon-to-nitrogen (C:N), carbon-to-sulfur (C:S), and nitrogen-to-sulfur (N:S) ratios in each sample (Ambrose 1990; DeNiro 1985; Nehlich and Richards 2009; van Klinken 1999). The wt. %C, wt. %N, and wt. %S values of each sample were analyzed during the isotopic analyses and provided by the laboratories. Atomic ratios were calculated using the following formulae:

$$\text{C:N} = \left(\frac{\text{wt. \%C}}{12.01}\right) \Big/ \left(\frac{\text{wt. \%N}}{14.01}\right) \tag{A.1}$$

$$\text{C:S} = \left(\frac{\text{wt. \%C}}{12.01}\right) \Big/ \left(\frac{\text{wt. \%S}}{32.07}\right) \tag{A.2}$$

$$\text{N:S} = \left(\frac{\text{wt. \%N}}{14.01}\right) \Big/ \left(\frac{\text{wt. \%S}}{32.07}\right) \tag{A.3}$$

Carbon and nitrogen values were considered to be uninfluenced by diagenesis if wt. %C was above 13 %, wt. %N was above 4.8 %, and C:N fell between 2.9 and 3.6 (Ambrose 1990; DeNiro 1985; van Klinken 1999). The sulfur values of mammalian bone collagen

were considered well preserved if wt. %S was between 0.15 and 0.35 %, C:S was between 300 and 900, and N:S was between 100 and 300 (Nehlich and Richards 2009). Because there is a higher amount of sulfur in fish bone collagen, these samples were considered well preserved if wt. %S was between 0.40 and 0.85 %, C:S was between 125 and 225, and N:S was between 40 and 80 (Nehlich and Richards 2009). The $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values of samples were removed from subsequent analyses if two or more indicators fell beyond acceptable values (Rand et al. 2015a). Finally, although previous studies have suggested that collagen yields below 1 % are too poorly preserved for analysis (van Klinken 1999; White et al. 1993), ultrafiltration is known to reduce collagen yields while producing viable collagen (Jørkov et al. 2007) and so this indicator was not used to detect diagenesis in this study.

A.6.2 Bone and Tooth Enamel Bioapatite

The mineral portions of bone and teeth are referred to as bioapatite. Bone bioapatite is a calcium phosphate similar in composition and structure to poorly crystalline hydroxyapatite (Glimcher et al. 1981). Because bone bioapatite is easily altered (Glimcher et al. 1981), it is more susceptible to diagenesis than is collagen (Krueger 1991). Researchers have proposed a number of techniques for establishing the integrity of bone apatite isotope values, including conducting Fourier Transform Infrared (FTIR) spectroscopy to measure the integrity of its crystalline structure (Nielsen-Marsh and Hedges 2000; Sillen and Sealy 1995; Wright and Schwarcz 1996), and similar techniques using attenuated total reflection (ATR) and diffuse reflectance infrared Fourier transform (DRIFT) spectroscopy have also been proposed (Beasley et al. 2014).

In this study, FTIR spectroscopy was unavailable and so it was not possible to assess the influence of diagenesis on the Nakum human bone and enamel samples. However, the preservation of bone apatite has been linked to collagen preservation (Kendall et al. 2018), and so only the oxygen and carbon values in bioapatite from bone samples that also produced viable collagen assessed using the techniques described in Section A.6.2 were considered for interpretation.

Finally, unlike bone bioapatite, tooth enamel is nonporous and has larger apatite crystals that makes it resistant to diagenesis (Quade et al. 1992; Trautz 1967). While some diagenesis may occur in tooth enamel (Schoeninger et al. 2003; Sponheimer and Lee-Thorp 1999), it is the preferred tissue for oxygen and strontium isotope analysis in archaeological investigations of human movement because it is more resistant than is bone apatite (Hoppe et al. 2003).

A.7 Establishing Environmental Isotopic Baseline Values for Identifying Nonlocal Individuals

The isotopic compositions of an individual's bones and teeth are derived from his or her diet and drinking water, which in turn reflect those of the local environment (Bentley 2006; Longinelli 1984; Richards et al. 2003; Nehlich 2015). Thus, the identification of nonlocal individuals from the isotopic values of archaeological human tissues is contingent upon known biologically available (bioavailable) isotope values in local environments as well as those from more distant areas. It is also necessary to remove nonlocal values from the data set to establish locally bioavailable isotopic baselines.

In the Maya region, there is sufficient variation in bioavailable $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values among different regions to permit identification of nonlocal individuals and local

isotopic baselines that characterize regional variation have been developed for much of this area (Hodell et al. 2004; Freiwald 2011a, 2011b; Lachniet and Patterson 2009; Miller Wolf and Freiwald 2018; Price et al. 2007, 2008, 2010, 2015; Trask et al. 2012). The predicted variability of $\delta^{34}S$ values throughout the Maya region has also recently been hypothesized (Rand and Grimes 2017). There are, however, several techniques for identifying nonlocal individuals, the efficiency of which are dependent upon the isotopic system of study.

One method for identifying whether an individual migrated is to identify a discrepancy between the isotopic values of his or her bones and teeth. This is because tooth enamel forms during childhood and therefore reflect the isotopic values of diet during the period of amelogenesis (AlQahtani et al. 2010; Moorrees et al. 1963a, 1963b; Nelson and Ash 2010), whereas bone remodels throughout life and therefore reflects the average isotopic values of foods and drinking water consumed from adolescence to the end of life, depending on the sampled bone and individual physiology in bone turnover rates (Hedges et al. 2007; Matsubayashi and Tayasu 2019; Parfitt 2001). However, isotopic fractionation may occur as elements are incorporated into different body tissues (Warinner and Tuross 2009), and this technique is only applicable to $\delta^{18}O$ values because sulfur isotopic studies in archaeology typically analyzed bone collagen (but see Goedert et al. 2020) and strontium present in bone bioapatite is highly susceptible to diagenesis (Budd et al. 2000; Hoppe et al. 2003). These limitations can be overcome through the comparison of the isotopic values of teeth that form at different ages, micro-samples of the same tooth, and bones that turnover at different rates from the same individual to identify whether he or she relocated multiple times during life (Agarwal 2016; Buikstra et al. 2004; Hrnčíř and Laffoon 2019;

Montgomery 2010; Montgomery et al. 2000; Schroeder et al. 2009; Schweissing and Grupe 2003; White et al. 2000; Wright 2013b).

Nonlocal individuals may also be identified as having bone and/or tooth enamel isotope values that differ from the isotopic baselines established for the burial location (see Grimstead et al. 2017). While isotopic baselines may be developed by analyzing modern geology, soil, plant, and water samples, bioavailable values are more accurately assessed by analyzing modern and archaeological animal tissues (Grimstead et al. 2017; Makarewicz and Sealy 2015; Price et al. 2002; Sillen et al. 1998). A baseline is conventionally developed by calculating the mean and two standard deviations of organic and inorganic environmental samples, and nonlocal individuals are identified as those who fall beyond this range (Price et al. 2002). While the same principle applies to stable sulfur isotope analysis, pollution since the industrial revolution has influenced modern $\delta^{34}S$ values, and so it is necessary to sample archaeological faunal bone to establish locally bioavailable sulfur isotope values (Richards et al. 2001; Trust and Fry 1992). Environmental baselines are useful for establishing bioavailable isotope values throughout a region; however, they may not always accurately reflect the human values due, for example, to the consumption of imported foods, marine foods, or foods grown in coastal areas influenced by marine isotope values deposited by sea spray (e.g., Fenner and Wright 2014; Grimstead et al. 2017; Freiwald et al. 2019; Guiry and Szpak 2020; Trask et al. 2012; Wright 2005a) and by imbibing different sources of water (Scherer et al. 2015).

The development of baselines for inferring human migration are also based on the understanding of how isotopes fractionate[12] during incorporation into consumer tissues, also known as diet-to-consumer offsets. Although strontium isotopes are fractionated during this process, it occurs below the level of detection using current instrumentation, so the isotopic values of human tissues directly reflect those of the environment in which the subsistence resources were obtained. Conversely, the diet-to-consumer offsets of stable oxygen isotopes are substantial and vary depending on the sampled tissue (France and Owsley 2015; Warinner and Tuross 2009). The fractionation of sulfur isotopes between diet and bone collagen ($\Delta^{34}S_{tissue\text{-}diet}$) requires further exploration. The original offset of +0.5 ± 2.4‰ compiled by Nehlich (2015:6) was based primarily on the offset between the diet and soft tissues of numerous species, mostly insects and fish, which may be inappropriate proxies for human $\Delta^{34}S_{tissue\text{-}diet}$ values. A more recent feeding experiment analyzing omnivorous pigs found a more substantial offset, wherein their femoral bone $\delta^{34}S$ values were 1.5 ‰ lower than the values of their diets (Webb et al. 2017). However, this study analyzed the $\delta^{34}S$ values of the whole diet, rather than just dietary methionine, and so the elevated $\delta^{34}S$ values of the feed could be caused by sulfur in carbohydrates or lipids. Finally, a study that specifically compared the bone collagen $\delta^{34}S$ values of ancient foxes and their prey from a sealed deposit found an average $\Delta^{34}S_{tissue\text{-}diet}$ value of –0.51 ± 0.03 ‰, which was considered negligible because it fell near or below analytical error (Krajcarz et al. 2019). Thus, sulfur isotope baselines developed from the $\delta^{34}S$ values of archaeological

[12] In kinetic reactions, the light isotopes react faster than the heavy isotopes, whereas in exchange reactions, the heavy isotopes concentrate where bonds are strongest (Fry 2006:12). This is called fractionation and it causes the isotopic values of the reactant and product entities to differ.

faunal remains are useful for characterizing isotopic variation throughout a region but may not accurately identify nonlocal human values until the sulfur isotope offset between diet and consumer tissues is better characterized.

Another approach to identifying nonlocal isotope values is comparison with previously published values from the same region, although this is only applicable in regions for which large databases are available (Lightfoot and O'Connell 2016:5). In the Maya region, numerous studies have resulted in compilations of strontium and oxygen values from different areas (Price et al. 2007, 2008, 2010). Unfortunately, the application of sulfur isotope analysis in the Maya region is in its infancy and comparative data sets are limited to a handful of studies (Awe et al. 2017; Green 2016; Rand et al. 2020a).

Finally, when baseline and comparative human data is unavailable, nonlocal individuals may be identified as those whose isotopic values are statistical outliers from the remaining values (Burton and Hahn 2016:119; Freiwald 2011a; Laffoon and Hoogland 2012; Lightfoot and O'Connell 2016; Montgomery et al. 2007; Knudson 2011; Wright 2005a; Chapters 3 and 4). As with local baselines developed from organic and inorganic environmental samples, nonlocal individuals are commonly identified as those whose isotopic values fall beyond two standard deviations of the mean of the human isotopic data set. However, when identifying nonlocal individuals using statistical techniques, it is important to note that the method, sample size, and distribution of the data will influence the number of outliers in a data set (Lightfoot and O'Connell 2016:6). For example, the presence of extreme outliers will skew the mean value, and so outliers should be removed prior to establishing a local baseline. Preferably, statistical techniques that are robust against outliers (e.g., interquartile range; see below) should be used to detect nonlocal

individuals in small and highly skewed data sets (Lightfoot and O'Connell 2016; Pearson and Grove 2013). This approach was used to identify and remove nonlocal individuals from the data sets prior to developing local $\delta^{34}S$ baseline values in this dissertation research.

A.8 Statistical Analyses

The specific statistical approaches and tests used in this research are summarized below, and readers are directed elsewhere for more detailed descriptions of these tests (Madrigal 1995; Otárola-Castillo and Torquato 2018; Shennan 1988; VanPool and Leonard 2011). All statistical analyses were performed in SPSS version 25 for Windows (IBM®).

Prior to analyzing comparative statistics, the distribution of the data was first tested for normality using the Shapiro-Wilk test (*W*; Shapiro and Wilk 1965). Most archaeological isotope studies are conducted on small data sets, the distribution of which are more influenced by the presence of outlying values, causing them to deviate from a normal, Gaussian distribution. Thus, nonparametric statistical tests were used for all data sets that did not follow a Gaussian distribution and for data sets that included less than eight values (Pearson and Grove 2013; see also Zimmerman and Zumbo 1993).

To identify outlying isotopic values, the interquartile range (IQR) rule was used, as it is more robust against the presence of outliers in small data sets. First, a boxplot was created in SPSS wherein the median is displayed as a solid line within the box, the interquartile range (IQR) between the first quartile (Q1) and third quartile (Q3) is represented by a box containing 50% of the data points, and the whiskers represent the IQR multiplied by 1.5 (IQR*1.5) subtracted from Q1 and added to Q3. Using the IQR rule,

outliers were identified as those that fell beyond the whiskers (i.e., IQR*1.5 – Q1 or IQR*1.5 + Q3) and extreme outliers fell beyond IQR*3 – Q1 or IQR*3 + Q3 (Tukey 1977).

To assess the correlation between groups (i.e., carbon and sulfur isotope values), the Pearson correlation coefficient (r) was used for normally distributed data and the Spearman's rank-order correlation (ρ) was used for data sets that did not follow a Gaussian distribution. A paired samples *t*-test (t) was performed to assess intra- and interlaboratory differences in normally distributed isotopic values from the same sample in Appendix B. If the groups did not follow a Gaussian distribution, or if there were fewer than eight samples in a group (Pearson and Grove 2013; see also Zimmerman and Zumbo 1993), the Wilcoxon signed-rank test (W) was used.

To evaluate differences in isotopic values between two groups (i.e., sites, protein source, etc.) the Independent Samples *t*-test (t) was used for normally distributed data and the Mann-Whitney U (U) test was used for non-parametric data. To evaluated differences between three or more groups, analysis of variance (ANOVA; F) was used for normally distributed data, and the Tukey and Games-Howell post hoc tests were used to identify differences between group pairs when variances were determined equal and unequal, respectively, using Levene's Tests for Equal Variances. To evaluated differences between three or more groups that were not normally distributed, the Kruskal-Wallis H (H) was used, and the significance of the resulting pairwise comparisons were automatically adjusted by the Bonferroni correction for multiple tests in SPSS.

Scholars have recently called into question the validity of null hypothesis significance testing (NHST) in archaeology and other disciplines and have explored alternative statistical tests such as bootstrapping and Bayesian statistics (Kline 2004;

Otárola-Castillo and Torquato 2018). However, these NHST approaches are the most commonly applied means of identifying differences in archaeological isotopic data analyses and were used in this research for comparability purposes. The confidence levels for these tests were set to 95 %, with resulting significance levels of $\alpha = 0.05$. Therefore, the null hypothesis (i.e., a data set followed a normal distribution, samples were derived from the same population, etc.) was rejected if the *p*-value was less than 0.05 and the statistical test was considered significant.

APPENDIX B

INTRA- AND INTER-LABORATORY COMPARABILITY OF ISOTOPIC RESULTS

B.1 Introduction

The assessment of isotopic data for the reconstruction of archaeological human movement and diet is based on the premise that results from samples prepared using different methods and obtained from different laboratories are directly comparable. The comparability of stable carbon, nitrogen, and oxygen isotopic results produced using different collagen extraction techniques (Fuller et al. 2014; Guiry et al. 2016; Jørkov et al. 2007; Liden et al. 1995; Rand et al. 2015a; Sealy et al. 2014; Szpak et al. 2017b; Yoder and Bartelink 2010) and among laboratories (Pestle et al. 2014) have been previously explored. However, the comparability of stable sulfur isotope values obtained within and among labs have yet to be assessed. Because collagen samples were prepared both with and without a sodium hydroxide (NaOH) treatment and analyzed by three different laboratories, it was necessary to assess the degree of intra-sample, as well as intra-laboratory and inter-laboratory variation in the isotopic results prior to their interpretation.

B.2 Materials and Methods

As part of a pilot study (Rand and Grimes 2017), the collagen of 20 human bone specimens from Caledonia was extracted for stable sulfur isotope analysis in 2015 using the methods described in Appendix A, excluding a NaOH treatment. The samples were analyzed at the Stable Isotope Laboratory (SIL) of Memorial University of Newfoundland (MUN; see Appendix A) and the analytical uncertainty is discussed in Appendix C.

Stable carbon and nitrogen isotope data from the same sample are necessary to evaluate whether the $\delta^{34}S$ results have been diagenetically altered (Nehlich and Richards 2009), and so previously published stable carbon and nitrogen isotope results (Rand 2012;

Rand et al. 2015b) were compared to the stable sulfur isotope results (Rand and Grimes 2017). However, stable carbon and nitrogen isotopic values may vary depending on how the collagen is extracted from the bone sample (Fuller et al. 2014; Guiry et al. 2016; Jørkov et al. 2007; Rand et al. 2015a; Sealy et al. 2014; Szpak et al. 2017b), and so the $\delta^{13}C$ and $\delta^{15}N$ values were reanalyzed from aliquots of the collagen samples prepared for stable sulfur isotope analysis. Six samples (2514, 2515, 2520, 2521, 2526, and 2528) had enough remaining collagen following stable sulfur isotope analysis for the analysis of stable carbon and nitrogen isotope ratios and concentrations. These, as well as collagen samples from Pacbitun, Moho Cay, Laguna de On Island and Shore, Caye Coco, Chanlacan, Caye Muerto, and Nakum were analyzed at MUN (Appendix A), and analytical uncertainty is described elsewhere (Appendix C). One sample was run in duplicate during the same analytical session and another nine were run in duplicate during different analytical sessions (Table B.1).

Because little or no collagen remained from the Caledonia samples following isotopic analysis at MUN, the collagen of 15 bone specimens (2516, 2517, 2518, 2519, 2522, 2523, 2525, 2527, 2528, 2530, 2531, 2532, 2533, 2535, and 2536) were again prepared for both carbon and nitrogen isotopic analysis and to assess inter-laboratory comparability of the isotopic results. The resamples have been assigned the designator "B" (i.e., 2518B) to differentiate them from the original collagen samples from the same bone specimen. The resamples were prepared in the same manner as the originals, but were treated with 0.1 M NaOH prior to gelatinization, as this treatment removes humic contaminants that influence $\delta^{13}C$ values (Ambrose 1990; Jørkov et al. 2007; Rand et al.

2015a; Sealy et al. 2014; Szpak et al. 2017b). The influence of a NaOH treatment on $\delta^{34}S$ values is, however, unknown.

Eight of the 15 original samples (2516, 2518, 2522, 2530, 2531, 2532, 2533, and 2535) had enough remaining collagen (1 mg) for stable carbon and nitrogen isotope analysis at the Ján Veizer Stable Isotope Laboratory at the University of Ottawa, along with eight Caledonia resamples (2517B, 2519B, 2523B, 2525B, 2527B, 2528B, 2529B, and 2534B), and samples from Vista Alegre, Oxtankah, Ichpaatun, San Migeulito, San Lorenzo, Xunantunich, San Bernabé, Tayasal, Caracol, Chac II, and Calakmul (Appendix A). Analytical uncertainty is discussed elsewhere (Appendix C).

Based on previous studies, it is assumed that stable carbon and nitrogen results obtained from different labs are directly comparable (Pestle et al. 2014). To examine interlaboratory variability in stable sulfur isotope analysis, aliquots of six original Caledonia bone collagen samples (2514, 2515, 2516, 2517, 2521, and 2526) and 13 resamples (2518B, 2519B, 2522B, 2523B, 2525B, 2527B, 2528B, 2530B, 2531B, 2532B, 2533B, 2535B, and 2536B) were sent to the Stable Isotope Laboratory in the Department of Earth and Planetary Sciences at the University of Tennessee for stable sulfur isotope analysis. Collagen samples from Pacbitun, Moho Cay, Laguna de On Island and Shore, Caye Coco, Caye Muerto, Chanlacan, Nakum, Vista Alegre, Oxtankah, Ichpaatun, and San Migeulito were also analyzed at Tennessee (Appendix A). Two samples were run in duplicate during the same analytical session and another 28 were run in duplicate during different analytical sessions (Table B.1).

Finally, the $\delta^{34}S$ and wt. % S values of the San Lorenzo, Xunantunich, San Bernabé, and Calakmul samples were analyzed by the Ján Veizer Stable Isotope Laboratory,

University of Ottawa (Appendix A). Analytical uncertainly was calculated in Appendix C, and no samples were run in duplicate due to the large amount of sample needed for analysis.

A Shapiro-Wilk test (*W*) was performed to determine whether the samples were normally distributed, after which paired samples *t*-tests (*t*) were performed to test whether the values of the same sample obtained by the same laboratory during different analytical sessions or from two different laboratories were significantly different. If the groups did not follow a Gaussian distribution, or if there were less than five samples in a group, the Wilcoxon signed-rank test (*W*) was used. All statistics were calculated in SPSS version 25 for Windows (IBM®) and results were considered statistically significant when $p < 0.05$.

B.3 Results

The stable carbon and nitrogen isotope results and concentrations of the Caledonia collagen samples prepared with and without a NaOH step and analyzed by two different laboratories are presented in Table B.1, and the stable sulfur isotope results and concentrations of the same samples analyzed by three laboratories are presented in Table B.2. The intra-sample, intra-laboratory, and inter-laboratory variation are discussed in more detail in the following sections.

B.3.1 Intra-Sample Variation of Stable Carbon and Nitrogen Results from Samples Treated with and without Sodium Hydroxide

Of the 15 Caledonia bone specimens that were resampled, seven (see Table B.3) had sufficient collagen remaining to assess the intra-sample variation in $\delta^{13}C$, $\delta^{15}N$, wt. %C, and wt. %N caused by differences in preparation methods. Only samples analyzed at the Ján Veizer SIL at the University of Ottawa are considered in the intra-sample variation

Table B.1: Stable carbon and nitrogen isotope and concentration values of the Caledonia samples organized by collagen extraction method that included or excluded a NaOH treatment and by laboratory that conducted the analyses.

Lab #	NaOH Treatment	δ^{13}C (VPDB, ‰)		δ^{15}N (AIR, ‰)		wt. %C		wt. %N	
		MUN	Ottawa	MUN	Ottawa	MUN	Ottawa	MUN	Ottawa
2514	No	–9.17	-	+8.10	-	43.26	-	15.31	-
2515	No	–10.56	-	+7.41	-	41.55	-	14.71	-
2516	No	-	-	-	+8.16	-	-	-	15.70
	Yes	-	–8.60	-	+8.04	-	42.40	-	15.40
2518	No	-	–8.81	-	+8.45	-	43.40	-	15.50
	Yes	-	–8.55	-	+8.86	-	47.90	-	17.20
2519	Yes	-	***–11.77***	-	***+11.62***	-	***38.25***	-	***13.76***
2520	No	–12.94	-	+8.36	-	31.34	-	11.09	-
2521	No	–7.82	-	+7.67	-	43.65	-	15.49	-
2522	No	-	–11.13	-	+8.79	-	39.30	-	14.13
2523	Yes	-	***–8.46***	-	***+10.52***	-	***43.90***	-	***15.85***
2525	Yes	-	–11.09	-	+9.92	-	42.40	-	15.40
2526	No	–7.99	-	+7.86	-	40.80	-	14.38	-
2527	Yes	-	–7.70	-	+8.75	-	41.00	-	14.77
2528	No	–12.02	-	+9.06	-	41.22	-	14.48	-
	Yes	-	–11.67	-	+9.71	-	41.80	-	15.10
2529	Yes	-	–8.33	-	+9.60	-	40.80	-	14.86
2530	No	-	–13.20	-	+8.56	-	42.80	-	15.50
	Yes	-	–13.22	-	+8.60	-	41.90	-	15.10
2531	No	-	–11.03	-	+8.61	-	40.90	-	14.66
	Yes	-	-10.88	-	+8.62	-	42.90	-	15.50
2532	No	-	–8.69	-	+9.61	-	41.90	-	15.20
	Yes	-	***–8.64***	-	***+9.22***	-	***43.25***	-	***15.75***
2533	No	-	–10.23	-	+9.26	-	43.00	-	15.60
	Yes	-	–10.24	-	+9.27	-	42.90	-	15.60
2534	Yes	-	–8.39	-	+10.62	-	42.90	-	15.60
2535	No	-	–13.10	-	+8.57	-	42.10	-	15.20
	Yes	-	–13.17	-	+8.52	-	40.70	-	14.80
2536	No	-	–12.26	-	+8.56	-	40.20	-	14.41

Note: Bolded and italicized values indicate averages based on duplicate analyses.

assessment to minimize variability potentially introduced by interlaboratory analyses. The differences in δ^{13}C values for the same sample prepared with and without a NaOH treatment ranged from –0.26 to +0.07 ‰ and the average pairwise difference was +0.06 ± 0.12 ‰. The δ^{15}N values ranged –0.41 ‰ to +0.39 ‰ with an average pairwise difference of +0.01

Table B.2: Stable sulfur isotope and concentration values of the Caledonia samples organized by laboratory and analytical session.

Lab #	MUN Session 1 (Sept 4, 2015)		MUN Session 2 (Sept 9, 2015)		Tennessee Session 1 (Nov 27, 2018)		Tennessee Session 2 (Nov 26, 2018)		Tennessee Session 3 (Nov 30, 2018)		Ottawa Session (May 2019)	
	δ^{34}S (‰)	wt. %S	δ^{34}S (‰)	wt. %S	δ^{34}S (‰)	wt. %S	δ^{34}S (‰)	wt. %S	δ^{34}S (‰)	wt. %S	δ^{34}S (‰)	wt. %S
2514	+10.27	0.21	+9.00	0.21	+9.77	0.22	-	-	-	-	-	-
2515	+12.43	0.21	+13.59	0.22	+11.54	0.22	-	-	-	-	-	-
2516	+10.14	0.22	+12.89	0.19	+10.91	0.20	-	-	-	-	-	-
2517	+11.73	0.24	+14.13	0.20	+11.82	0.20	-	-	-	-	-	-
2518	+12.25	0.24	+11.01	0.23	+10.96	0.22	-	-	-	-	-	-
2519	+10.74	0.20	+9.67	0.21	+9.43	0.20	-	-	-	-	-	-
2521	+12.93	0.20	+11.09	0.22	+12.72	0.30	-	-	-	-	-	-
2522	+8.90	0.20	-	-	+9.89	0.20	-	-	-	-	-	-
2523	+12.69	0.20	+12.66	0.19	+13.37	0.19	-	-	-	-	-	-
2525	+13.21	0.21	-	-	+12.82	0.20	-	-	-	-	-	-
2526	+12.12	0.20	-	-	+11.62	0.21	-	-	-	-	-	-
2527	+12.62	0.21	-	-	+12.14	0.19	-	-	-	-	-	-
2528	+13.73	0.22	+13.73	0.20	+12.79	0.20	-	-	-	-	-	-
2530	-	-	+7.17	0.20	+7.98	0.20	-	-	-	-	-	-
2531	-	-	+10.21	0.19	+10.29	0.21	-	-	-	-	-	-
2532	- -	- -	+14.21 +13.13	0.20 0.17	+12.25	0.19	- -	- -	- -	- -	- -	- -
2533	-	-	+13.78	0.18	+12.10	0.20	-	-	-	-	-	-
2535	-	-	+7.10	0.20	+7.87	0.19	-	-	-	-	-	-
2536	-	-	+10.37	0.19	+11.82	0.23	-	-	-	-	-	-
4406	-	-	-	-	-	-	+11.75	0.19	+11.42	0.20	+14.10	0.15

± 0.24 ‰ (Table B.3). Intra-sample differences in carbon and nitrogen concentrations were more variable, with wt. %C ranging from –4.50 to +1.40 % with a mean pairwise difference of –0.91 ± 2.19 % and wt. %N ranging from –1.70 to +0.40 % with a mean pairwise difference of –0.28 ± 0.79 % (Table B.3). All groups were normally distributed (Table B.4) and so paired-samples *t*-tests were used to assess differences between samples (Table B.5).

Although on average the samples prepared without a NaOH treatment had slightly higher δ^{13}C and δ^{15}N values and lower wt. %C and wt. %N than samples of the same bone

Table B.3: Intra-sample variability of $\delta^{13}C$ and $\delta^{15}N$ values from Caledonia samples of the same bone treated with and without NaOH during collagen extraction.

Lab #	Without NaOH Treatment				With NaOH Treatment ("B")				Δ(Without-With)			
	$\delta^{13}C$ (VPDB, ‰)	wt. %C	$\delta^{15}N$ (AIR, ‰)	wt. %N	$\delta^{13}C$ (VPDB, ‰)	wt. %C	$\delta^{15}N$ (AIR, ‰)	wt. %N	$\delta^{13}C$ (VPDB, ‰)	wt. %C	$\delta^{15}N$ (AIR, ‰)	wt. %N
2516	*	*	+8.16	15.70	–8.60	42.40	+8.04	15.40	*	*	+0.12	+0.30
2518	–8.81	43.40	+8.45	15.50	–8.55	47.90	+8.86	17.20	–0.26	–4.50	–0.41	–1.70
2530	–13.20	42.80	+8.56	15.50	–13.22	41.90	+8.60	15.10	+0.02	+0.90	–0.04	+0.40
2531	–11.03	40.90	+8.61	14.66	–10.88	42.90	+8.62	15.50	–0.15	–2.00	–0.01	–0.84
2532	–8.69	41.90	+9.61	15.20	***–8.64***	***43.25***	***+9.22***	***15.75***	–0.05	–1.35	+0.39	–0.55
2533	–10.23	43.00	+9.26	15.60	–10.24	42.90	+9.27	15.60	+0.01	+0.10	–0.01	+0.00
2535	–13.10	42.10	+8.57	15.20	–13.17	40.70	+8.52	14.80	+0.07	+1.40	+0.05	+0.40
$\bar{x}$									+0.06	–0.91	+0.01	–0.28
σ									0.12	2.18	0.24	0.79
n									6	6	7	7

Note: Bolded and italicized values represent an average of sample duplicates run during the same analytical session.
***** The software crashed after the analysis of nitrogen from sample 2516 prepared without a NaOH treatment and so no carbon data is available for this sample.

Table B.4: Shapiro-Wilk test for normality of the Caledonia samples prepared with and without a NaOH treatment.

Group	*W*	*df*	*p*
$\delta^{13}C$ without NaOH	0.879	6	0.264
wt. %C without NaOH	0.955	6	0.784
$\delta^{13}C$ with NaOH	0.872	6	0.232
wt. %C with NaOH	0.831	6	0.109
$\delta^{15}N$ without NaOH	0.876	7	0.209
wt. %N without NaOH	0.878	7	0.219
$\delta^{15}N$ with NaOH	0.939	7	0.629
wt. %N with NaOH	0.841	7	0.102

Note: The null hypothesis that the sample follows a normal distribution is rejected if $p < 0.05$.

Table B.5: Paired samples *t*-test results of values from original samples and resamples.

Pair	*t*	*df*	*p*
$\delta^{13}C$ (VPDB, ‰)	–1.189	5	0.288
$\delta^{15}N$ (AIR, ‰)	0.143	6	0.891
wt. %C	–1.018	5	0.356
wt. %N	–0.952	6	0.378

Note: The null hypothesis that the mean values of the paired samples are similar is rejected if $p < 0.05$.

prepared with the treatment (Table B.3), these differences were not statistically significant (Table B.5). Therefore, it was determined that the $\delta^{13}C$ and $\delta^{15}N$ values from samples of collagen from the same bone prepared with and without a NaOH treatment are statistically comparable in this study.

Unfortunately, insufficient collagen remained from the original samples to test the relationship between $\delta^{34}S$ and %S of samples treated with and without a NaOH step during collagen extraction. Based on the carbon and nitrogen results, the sulfur values are assumed to be comparable between treatment methods pending further experimental investigation.

B.3.2 Intra-Laboratory Variation of Stable Sulfur Isotope Values

Intra-laboratory variation in isotopic and concentration values is monitored using replicates of check standards and samples during each analytical session. Szpak et al. (2017a) provide a detailed methodology for calculating analytical precision based on replicate analyses. However, most replicate analyses of stable sulfur isotopes and concentrations included in this study were run during separate analytical sessions at both MUN and Tennessee. Intra-laboratory variation was thus assessed by analyzing aliquots of samples prepared using the same technique at the same laboratory but during separate analytical sessions. As a result, the Caledonia samples prepared without a NaOH step were used to assess the intra-laboratory variation of sulfur isotopes and concentrations at MUN, but samples from multiple Maya sites prepared at MUN using a NaOH treatment were used to assess the intra-laboratory variation at Tennessee. The inclusion or exclusion of a NaOH treatment should not impact the assessment of intra-laboratory variation.

Although, sample replicates analyzed during the same session are included in Table B.6 along with the duplicates run during separate analytical sessions, the former were excluded from the intra-laboratory assessment presented here, as they speak to the precision specific to the samples discussed by Szpak et al. (2017a) and presented in Appendix C. It is assumed that the duplicate samples run for stable carbon and nitrogen isotope analysis at Ottawa were analyzed during the same analytical session and so the discussion of intra-laboratory variation presented here is restricted to stable sulfur isotope values and concentrations.

Duplicate samples run at each lab were grouped by analytical session (i.e., samples whose duplicates were run on Nov. 28 and Nov. 30 versus samples whose duplicates were run on Nov. 26 and Nov. 30) for statistical comparison. The δ^{34}S values of five pairs of groups and the %S of three were normally distributed (Table B.7) and assessed using the paired samples *t*-test (Table B.8). Two of the five comparisons of the δ^{34}S values and one of the three comparisons of wt. %S values between normally distributed groups were statistically significant (Table B.9); however, the sample sizes were small ($n < 5$) and so they were reassessed using the nonparametric Wilcoxon signed rank test (Pearson and Grove 2013).

The differences in δ^{34}S values from the nine samples run during different analytical session at MUN ranged from –2.75 to +1.84 ‰ with a mean pairwise difference of –0.10 ± 1.67 ‰, while the wt. %S were more homogenous, ranging from –0.02 to +0.04 % with a mean pairwise difference of +0.01 ± 0.02 %. The differences in δ^{34}S values from the 14 samples analyzed with and without dilution at Tennessee ranged from –1.98 to +3.01 ‰ with a mean pairwise difference of +0.32 ± 1.16 ‰ for the 11 samples run on Nov. 8 and

Table B.6: The $\delta^{34}S$ and wt. %S values of samples run in duplicate by lab and session.

Duplicate Analyses Dates / Lab #	Session 1		Session 2		$\Delta_{session1-session2}$	
	$\delta^{34}S$ (‰, VCDT)	wt. %S	$\delta^{34}S$ (‰, VCDT)	wt. %S	$\delta^{34}S$ (‰, VCDT)	wt. %S
MUN Sept. 4 vs. Sept. 9						
2514	+10.27	0.21	+9.00	0.21	+1.27	0.00
2515	+12.43	0.21	+13.59	0.22	–1.16	–0.01
2516	+10.14	0.22	+12.89	0.19	–2.75	+0.03
2517	+11.73	0.24	+14.13	0.20	–2.40	+0.04
2518	+12.25	0.24	+11.01	0.23	+1.24	+0.01
2519	+10.74	0.20	+9.67	0.21	+1.07	–0.01
2521	+12.93	0.20	+11.09	0.22	+1.84	–0.02
2523	+12.69	0.20	+12.66	0.19	+0.03	+0.01
2528	+13.73	0.22	+13.73	0.20	0.00	+0.02
$\bar{x}$					–0.10	+0.01
σ					1.67	0.02
n					9	9
MUN Sept 9						
2532	+14.21	0.20	+13.13	0.17	+1.08	+0.03
Tennessee with dilution (Nov. 8) vs. without dilution (Nov. 14)						
4260	+11.41	0.24	+13.39	0.24	–1.98	0.00
4261	+9.61	0.29	+9.44	0.28	+0.17	+0.01
4262	+13.28	0.24	+13.38	0.23	–0.10	+0.01
4263	+12.70	0.32	+12.92	0.32	–0.22	0.00
4267	+8.81	0.23	+8.23	0.23	+0.58	0.00
4268	+10.94	0.22	+10.54	0.23	+0.40	–0.01
4270	+12.48	0.21	+11.97	0.21	+0.51	0.00
4271	+14.24	0.25	+13.79	0.27	+0.45	–0.01
4272	+13.72	0.23	+10.71	0.23	+3.01	0.00
4273	+12.66	0.21	+12.01	0.20	+0.65	+0.01
4274	+17.13	0.50	+17.12	0.50	+0.02	0.00
$\bar{x}$					+0.32	0.00
σ					1.16	0.01
n					11	11
Tennessee with dilution (Nov. 8) vs. without dilution (Nov. 30)						
4255	+13.05	0.22	+11.90	0.20	+1.15	+0.02
4262	+13.28	0.24	+12.30	0.22	+0.98	+0.02
4270	+12.48	0.21	+11.73	0.20	+0.74	+0.01
$\bar{x}$					+0.96	+0.02
σ					0.20	0.01
n					3	3

Table B.6 Continued.

Duplicate Analyses Dates / Lab #	Session 1		Session 2		$\Delta_{session1-session2}$	
	$\delta^{34}S$ (‰, VCDT)	%S	$\delta^{34}S$ (‰, VCDT)	%S	$\delta^{34}S$ (‰, VCDT)	%S
Tennessee Nov. 14 vs. Nov. 30						
4320	+13.40	0.21	+12.03	0.21	+1.37	+0.01
4328	+14.40	0.21	+13.47	0.20	+0.93	+0.01
2462	+13.38	0.23	+12.30	0.22	+1.08	+0.01
4270	+11.97	0.21	+11.73	0.20	+0.23	+0.01
$\bar{x}$					+0.90	+0.01
σ					0.48	0.00
n					4	4
Tennessee Nov. 25 vs. Nov. 30						
4294	+14.18	0.20	+13.27	0.18	+0.91	+0.02
4303	+14.12	0.21	+13.53	0.18	+0.60	+0.03
4305	+9.38	0.22	+6.77	0.20	+2.61	+0.01
$\bar{x}$					+1.37	+0.02
σ					1.08	0.01
n					3	3
Tennessee Nov. 26 vs. Nov. 30						
4332	+14.02	0.18	+13.06	0.20	+0.96	–0.01
4406	+11.75	0.19	+11.42	0.20	+0.33	–0.01
4522	-0.18	0.49	-2.34	0.50	+2.16	–0.01
4533	+13.14	0.23	+12.14	0.24	+1.00	–0.01
$\bar{x}$					+1.11	–0.01
σ					0.76	0.00
n					4.00	4.00
Tennessee Nov. 27 vs. Nov. 30						
4553	–1.14	0.34	–4.47	0.40	+3.33	–0.06
4555	+13.24	0.26	+11.27	0.26	+1.97	0.00
$\bar{x}$					+2.65	–0.03
σ					0.96	0.04
n					2.00	2.00
Tennessee Nov. 28 vs. Nov. 30						
2558	+11.82	0.20	+11.08	0.19	+0.74	+0.01
2561	+13.42	0.19	+13.17	0.18	+0.25	+0.01
3451	+16.71	0.21	+14.20	0.20	+2.51	+0.02
3458	+13.30	0.18	+13.22	0.16	+0.08	+0.02
4155	+14.66	0.21	+13.67	0.19	+0.99	+0.02
$\bar{x}$					+0.91	+0.01
σ					0.96	0.00
n					5.00	6.00

Table B.6 Continued.

Duplicate Analyses Dates / Lab #	Session 1		Session 2		$\Delta_{session1-session2}$	
	$\delta^{34}S$ (‰, VCDT)	%S	$\delta^{34}S$ (‰, VCDT)	%S	$\delta^{34}S$ (‰, VCDT)	%S
Tennessee Nov. 30						
4161	+8.23	0.21	+8.99	0.21	–0.76	0.00
4192	+4.43	0.25	+4.69	0.25	–0.26	0.00
$\bar{x}$					–0.51	0.00
σ					0.36	0.00
n					2.00	3.00

Table B.7: Results of the Shapiro-Wilk (W) test for normality of the $\delta^{34}S$ and wt. %S of samples run in duplicate by analytical session.

Comparison	Group	$\delta^{34}S$			wt. %S		
		W	***df***	***p***	***W***	***df***	***p***
MUN Sept 4 vs. MUN Sept. 9	MUN Sept 4	0.936	9	0.540	0.849	9	0.072
	MUN Sept. 9	0.915	9	0.356	0.938	9	0.577
Tennessee with dilution (Nov. 8) vs. without dilution (Nov. 14)	Tennessee Nov. 8	0.967	11	0.860	0.671	11	***0.000***
	Tennessee Nov. 14	0.966	11	0.841	0.683	11	***0.000***
Tennessee with dilution (Nov. 8) vs without dilution (Nov. 30)	Tennessee Nov. 8	0.942	3	0.534	0.988	3	0.794
	Tennessee Nov. 30	0.949	3	0.567	0.778	3	0.062
Tennessee Nov. 14 vs. Nov 30	Tennessee Nov. 14	0.935	4	0.624	0.714	4	***0.017***
	Tennessee Nov. 30	0.882	4	0.347	0.815	4	0.131
Tennessee Nov. 25 vs. Nov. 30	Tennessee Nov. 25	0.758	3	***0.019***	0.998	3	0.915
	Tennessee Nov. 30	0.779	3	0.065	0.750	3	***0.000***
Tennessee Nov. 26 vs. Nov. 30	Tennessee Nov. 26	0.754	4	***0.042***	0.748	4	***0.037***
	Tennessee Nov. 30	0.716	4	***0.017***	0.745	4	***0.034***
Tennessee Nov. 28 vs. Nov. 30	Tennessee Nov. 28	0.959	5	0.798	0.957	5	0.790
	Tennessee Nov. 30	0.855	5	0.212	0.911	5	0.473

Note: Bolded and italicized values are significant at the α=0.05 level, meaning that the null hypothesis of normality is rejected, and nonparametric tests are required to assess the data.

Table B.8: Results of paired samples t-test for $\delta^{34}S$ and %S values of samples analyzed in duplicate.

Pair	Variable	*t*	*df*	*p*
MUN Sept. 4 vs. Sept. 9	$\delta^{34}S$	-1.72	8	0.868
	wt. %S	1.175	8	0.274
Tennessee Nov. 8 vs. Nov. 14	$\delta^{34}S$	0.912	10	0.383
Tennessee Nov. 8 vs. 30	$\delta^{34}S$	8.164	2	***0.015****
	wt. %S	3.863	2	0.061
Tennessee Nov. 14 vs. Nov. 30	$\delta^{34}S$	3.742	3	***0.033****
Tennessee Nov. 28 vs. Nov. 30	$\delta^{34}S$	2.122	4	0.101
	wt. %S	6.866	4	***0.002****

Note: Bolded and italicized values are significant at the α=0.05 level.
*Because this was based on a small sample size (n<5) a non-parametric Wilcoxon signed rank test was also used to assess the difference.

Table B.9: Results of the Wilcoxon Signed Rank Test of the $\delta^{34}S$ and wt. %S values of samples run in duplicate.

Pair	Variable	*W*	*p*
Tennessee Nov. 8 vs. Nov. 14	wt. %S	-0.102	0.919
Tennessee Nov. 8 vs. Nov. 30	$\delta^{34}S$	-1.604	0.109
Tennessee Nov. 14 vs. Nov. 30	$\delta^{34}S$	-1.826	0.068
	wt. %S	-1.826	0.068
Tennessee Nov. 25 vs. Nov. 30	$\delta^{34}S$	-1.604	0.109
	wt. %S	-1.604	0.109
Tennessee Nov. 26 vs. Nov. 30	$\delta^{34}S$	-1.826	0.068
	wt. %S	-1.841	0.066
Tennessee Nov. 28 vs. Nov. 30	wt. %S	-2.023	***0.043***

Note: Bolded and italicized values are significant at the 0.05 level, meaning that they are significantly different.

Nov. 14 and +0.96 ± 0.20 ‰ for the 3 samples run on Nov. 8 and Nov. 14 (Table B.6). The differences in the wt. %S of these samples were again more homogenous and ranged from –0.01 to +0.02 %, with a mean pairwise difference of 0.00 ± 0.01 % for the 11 samples run on Nov. 8 and Nov. 14, whereas the mean pairwise difference in the wt. %S of the three samples run on Nov. 8 and Nov. 30 was +0.02 ± 0.01 % (Table B.6). Finally, the differences in $\delta^{34}S$ values of the 20 samples run on different days at Tennessee without dilution ranged from –0.76 to +3.33 ‰ with an average pairwise difference of +1.05 ± 1.03‰, whereas the differences in their wt. %S values ranged from –0.06 to +0.03 % with an average pairwise difference of 0.00 ± 0.02% (see Table B.6).

Excluding the wt. %S values of sample duplicates analyzed at Tennessee on November 28 and 30, which were significantly different (Z = –2.02, p = 0.04), the differences between all other sample duplicates assessed using the Wilcoxon signed rank test were not statistically significant (Table B.9). Therefore, the decision to average duplicate samples run at the same laboratory is justified by the general lack of statistically significant differences between duplicate samples run on different days.

B.3.3 Inter-Laboratory Variation of Stable Sulfur Isotope Values

Finally, it was necessary to assess variation in the isotopic results among laboratories to ensure that δ^{34}S and wt. %S values obtained from different labs are comparable. Based on the lack of statistically significant differences between the δ^{34}S and %S values from duplicate samples analyzed during separate sessions, the values from the sample replicates analyzed during separate sessions at MUN were averaged to obtain a single value. Similarly, the lack of statistically significant differences between the δ^{34}S and wt. %S values from the original samples prepared without a NaOH step and the resamples prepared with the NaOH step justify their comparison in the following assessment, because although only the originals were analyzed at MUN, both were analyzed at Tennessee. The compared values can be found in Table B.10 and are visualized in Figure B.1. Only a single sample was analyzed at both Tennessee and Ottawa, and so it was excluded from further statistical analyses.

The difference in the δ^{34}S values between the 19 samples run at MUN and Tennessee ranged from –1.45 to +1.68 ‰ with a mean pairwise difference of +0.23 ± 0.93 ‰ and the differences in wt. %S for the same samples ranged from –0.09 to +0.02 % with a mean pairwise difference of –0.01 ± 0.02 % (Table B.10). The pairwise difference in the δ^{34}S value of the only sample run at Tennessee and Ottawa was –2.52 ‰ and the difference in the wt. %S was +0.04 % (Table B.10).

Shapiro-Wilk tests for normality found that although the wt. %S values from MUN ($W(19) = 0.964$, $p = 0.643$) and δ^{34}S values from Tennessee ($W(19) = 0.924$, $p = 0.135$) were normally distributed, the wt. %S values from Tennessee ($W(19) = 0.671$, $p = 0.000$) and the δ^{34}S values from MUN ($W(19) = 0.901$, $p = 0.050$) were not. Therefore, the

Table B.10: The $\delta^{34}S$ and wt. %S values for sample aliquots analyzed at MUN, Tennessee, and Ottawa.

Lab #	MUN		Tennessee		Ottawa		$\Delta^{34}S$	$\Delta^{34}S$	Δ%S	Δ%S
	$\delta^{34}S$ (VCDT, ‰)	wt. %S	$\delta^{34}S$ (VDCT, ‰)	wt. %S	$\delta^{34}S$ (VCDT, ‰)	wt. %S	MUN-Tennessee	Tennessee-Ottawa	MUN-Tennessee	Tennessee-Ottawa
2514	+9.64	0.21	+9.77	0.22	-	-	–0.14	-	–0.01	-
2515	+13.01	0.21	+11.54	0.22	-	-	1.48	-	–0.01	-
2516	+11.52	0.20	+10.91	0.20	-	-	0.60	-	0.00	-
2517	+12.93	0.22	+11.82	0.20	-	-	1.11	-	0.02	-
2518	+11.63	0.23	***+10.96***	***0.22***	-	-	0.67	-	0.01	-
2519	+10.21	0.21	***+9.43***	***0.20***	-	-	0.77	-	0.00	-
2521	+12.01	0.21	+12.72	0.30	-	-	–0.71	-	–0.09	-
2522	+8.90	0.20	***+9.89***	***0.20***	-	-	–0.99	-	0.00	-
2523	+12.68	0.19	***+13.37***	***0.19***	-	-	–0.70	-	0.00	-
2525	+13.21	0.21	***+12.82***	***0.20***	-	-	0.39	-	0.00	-
2526	+12.12	0.20	+11.62	0.21	-	-	0.50	-	0.00	-
2527	+12.62	0.21	***+12.14***	***0.19***	-	-	0.48	-	0.02	-
2528	+13.73	0.21	***+12.79***	***0.20***	-	-	0.94	-	0.01	-
2530	+7.17	0.20	***+7.98***	***0.20***	-	-	–0.81	-	0.00	-
2531	+10.21	0.19	***+10.29***	***0.21***	-	-	–0.08	-	–0.02	-
2532	+13.67	0.19	***+12.25***	***0.19***	-	-	1.42	-	–0.01	-
2533	+13.78	0.18	***+12.10***	***0.20***	-	-	1.68	-	–0.02	-
2535	+7.10	0.20	***+7.87***	***0.19***	-	-	–0.77	-	0.01	-
2536	+10.37	0.19	***+11.82***	***0.23***	-	-	–1.45	-	–0.03	-
4406	-	-	+11.58	0.20	+14.10	0.15	-	–2.52	-	0.04
$\bar{x}$							0.23	–2.52	–0.01	0.04
σ							0.93		0.02	
n							19	1	19	1

Note: Duplicate analyses have been averaged to obtain a single value.
Note: Bolded and italicized values were obtained from resamples prepared using a NaOH treatment.

nonparametric Wilcoxon rank order test was used to assess differences between the labs. The $\delta^{34}S$ values obtained from MUN were not statistically different from those obtained from Tennessee (Z= –0.845, p = 0.398), nor were the wt. %S values obtained from each lab (Z = –0.654, p = 0.513). Therefore, the data obtained from MUN and Tennessee are comparable in this study.

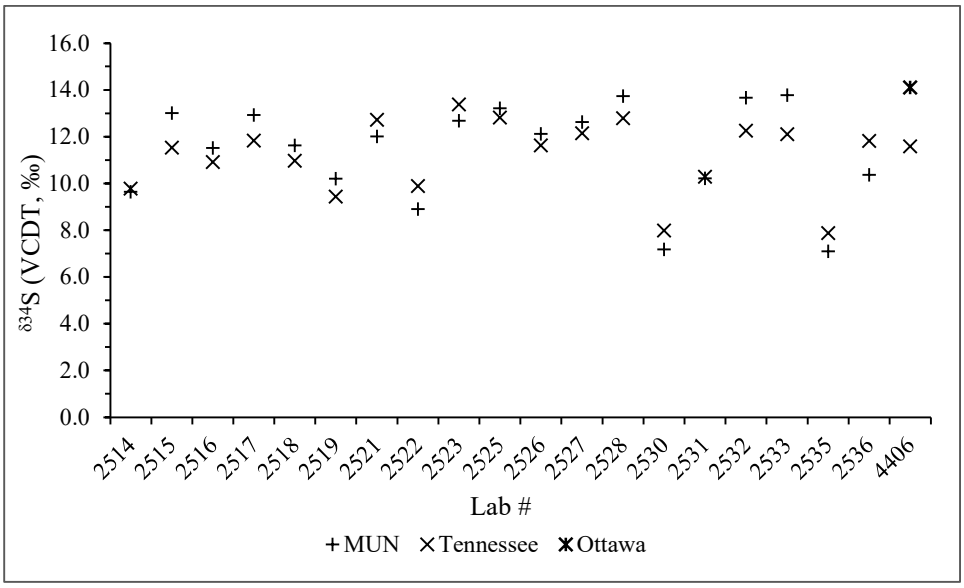

Figure B.1: Stable sulfur isotope values for the same sample analyzed at different laboratories.

B.4 Summary and Conclusions

On average, the samples prepared without a NaOH treatment had slightly higher $\delta^{13}C$ and $\delta^{15}N$ values and lower wt. %C and wt. %N than samples of the same bone prepared with the treatment (Table B.3). These results contrast with previous studies that have found wt. %C to be lower, $\delta^{13}C$ values to be higher, and $\delta^{15}N$ and wt. %N to be unaffected by treatment with NaOH (Sealy et al. 2014; Jørkov et al. 2007), which may relate to the addition of an ultrafiltration step during collagen extraction. Regardless, the differences observed in this study are not statistically significant (Section B.2.1), and so the comparison of the $\delta^{13}C$ and $\delta^{15}N$ values from samples prepared with and without a NaOH step was deemed reasonable in this study. Unfortunately, there was insufficient collagen remaining from the original samples to test the effects of NaOH treatment on the sulfur concentration and isotopic values. Here, it is tentatively assumed that the differential treatment will not

significantly influence the sulfur results, although future experimentation is required to justify this assumption.

Although sample replicates should be analysed in the same analytical sequence (Jardine and Cuniak 2005), the majority of the $\delta^{34}S$ and wt. %S values of duplicate samples were analyzed during different analytical sessions at both MUN and Tennessee. Fortunately, the differences between the duplicate values were not found to be statistically significant (Section B.2.2) and so it was deemed appropriate to average the duplicate values from sample replicates run at the same lab regardless of analytical session, to generate a single value for each sample.

Finally, it was necessary to ascertain whether values from the same sample analyzed by different labs were comparable. After averaging the $\delta^{34}S$ and wt. %S values from the duplicate analyses at each lab, no statistically significant differences were found between the $\delta^{34}S$ and wt. %S values from the same sample analyzed at MUN and Tennessee (Section B.2.3). Therefore, the isotopic values obtained from aliquots of the same bone sample analyzed at different laboratories are considered comparable in this study. The stable sulfur isotopes of only one sample were analyzed by both Tennessee and Ottawa, and although the difference in the wt. %S from each lab was low (+0.04 %), the difference between the $\delta^{34}S$ values was the largest reported in this study (–2.52 ‰) and exceeded the analytical uncertainty of all analyses (Appendix C). The difference may be the result of differing analytical approaches, as both MUN and Tennessee combusted samples of collagen weighing 5 to 15 mg with 1 mg vanadium pentoxide (V_2O_5) and had comparable results, whereas 25 to 55 mg of sample was combusted with at least twice its weight of sucrose at the University of Ottawa. Thus, the $\delta^{34}S$ values from bone collagen samples analyzed at

MUN and Tennessee are considered directly comparable, whereas the values from samples analyzed at Ottawa may be slightly higher. However, this observation is based on a single sample and additional research is necessary to further investigate interlaboratory comparability of δ^{34}S and %S values from archaeological bone collagen.

APPENDIX C

Analytical Uncertainty of the Isotopic Measurements

C.1 Introduction

Reporting analytical uncertainty is necessary for comparing isotopic data generated by separate laboratories under differing conditions (Szpak et al. 2017a). This is because differences among isotopic values, whether among individuals or sites, must exceed analytical uncertainty to be meaningfully interpretable rather than the result of analytical or human error. Analytical uncertainty was calculated following the method proposed by Szpak et al. (2017a) and is explained in detail in Appendix A. Briefly, analytical accuracy (*u(bias)*) reflects systematic measurement errors and the degree to which the δ-values of check standards deviate from their known values. Analytical precision ($u(R_w)$ reflects the repeatability of measurements and is calculated using the variation of δ-values from both standards (measurement precision; s_{srm}) and sample replicates (precision specific to sample replicates; s_{rep}) included in the analytical sessions. The analytical precision and accuracy are then used to calculate total standard uncertainty (u_c). Using the analytical data provided by each laboratory and presented in the following tables, the total analytical uncertainty for each laboratory at which samples in this dissertation were analyzed is presented below.

C.2 Stable Carbon and Nitrogen Isotope Analysis of Bone Collagen

C.2.1 Stable Isotope Laboratory, Memorial University of Newfoundland

Stable carbon and nitrogen isotopic and elemental compositions of six Caledonia samples prepared without a NaOH treatment (Lab #s 2514, 2515, 2520, 2521, 2526, and 2528), as well samples from as Pacbitun (n = 34), Moho Cay (n = 1), Laguna de On Island (n = 46), Laguna de On Shore (n = 1), Caye Coco (n = 33), Chanlacan (n = 19), Caye

Muerto (n = 3), and Nakum (n = 22) were analyzed at the Stable Isotope Laboratory (SIL) at the Memorial University of Newfoundland (MUN; see Appendix A).

Stable carbon and nitrogen isotope compositions were calibrated relative to VPDB (δ^{13}C) and AIR (δ^{15}N) using EDTA #2, USGS62, and IAEA-N-2 (Table C.1). The internal standards listed in Table C.1 were used to monitor internal accuracy and precision. Their isotopic compositions represent long term averages calibrated to VPDB and AIR with USGS62 and EDTA #2 (Alison Pye, personal communication 2018). The means and standard deviations of the δ^{13}C and δ^{15}N values for the check and calibration standards as well as the number of standards included in each analytical session are presented in Table C.2. Measurement precision (s_{srm}) as calculated by repeated measurements of the standards was ±0.15 ‰ for δ^{13}C (df = 134) and ±0.10 ‰ for δ^{15}N (df = 135) and measurement accuracy ($u(bias)$) was ±0.23 ‰ for δ^{13}C and ±0.20 ‰ for δ^{15}N.

The carbon and nitrogen isotope ratios and compositions of one bone sample was analyzed in triplicate in each of the six analytical session (6/146), the results of which are presented in Table C.3. The measurement precision specific to the samples was ±0.10 ‰ for δ^{13}C and ±0.12 ‰ for δ^{15}N (df = 12). Based on the pooled standard deviations of all

Table C.1: Standard reference materials used for calibration of δ^{13}C relative to VPDB and δ^{15}N relative to AIR and to monitor (check) internal accuracy and precision by the Stable Isotope Lab (MUN).

Standard	Material	Type	Accepted δ^{13}C (‰, VPDB)	Accepted δ^{15}N (‰, AIR)
EDTA #2	EDTA	Calibration	-40.38±0.01	–0.83 ± 0.04
USGS-62	Caffeine	Calibration	-14.79±0.04	+20.17 ± 0.06
IAEA-N-2	Ammonium Sulfate	Calibration		+20.32 ± 0.09
G-9	L-glutamic acid	Check	-26.74±0.06	–2.77 ± 0.18
G-32	Sulfanilamide	Check	-28.96±0.22	–3.62 ± 0.25
G-40	B2155 (protein)	Check	-27.03±0.13	+5.97 ± 0.08

Table C.2: Mean and standard deviation of all check and calibration standards for all carbon and nitrogen analytical sessions conducted by the Stable Isotope Lab (MUN).

Session	Standard	δ^{13}C (‰, VPDB)	N	δ^{15}N (‰, AIR)	N
May 28 2018	EDTA#2	−40.38 ± 0.02	6	−0.83 ± 0.04	6
May 29 2018	EDTA#2	−40.38 ± 0.02	6	−0.83 ± 0.06	6
May 30 2018	EDTA#2	−40.38 ± 0.1	6	−0.83 ± 0.07	6
May 31 2018	EDTA#2	−40.38 ± 0.16	6	−0.83 ± 0.09	6
June 1 2018	EDTA#2	−40.38 ± 0.19	5	−0.83 ± 0.05	5
Jan 30 2019	EDTA#2	−40.38 ± 0.16	6	−0.83 ± 0.03	6
May 28 2018	G-40	−27.25 ± 0.03	4	+5.93 ± 0.09	4
May 29 2018	G-40	−27.24 ± 0.04	4	+5.90 ± 0.10	4
May 30 2018	G-40	−27.29 ± 0.04	4	+6.00 ± 0.09	4
May 31, 2018	G-40	−27.27 ± 0.22	4	+5.95 ± 0.08	4
June 1 2018	G-40	−27.34 ± 0.16	3	+5.98 ± 0.11	3
Jan 30 2019	G-40	−27.24 ± 0.18	6	+6.09 ± 0.08	6
May 28 2018	G-9	−26.64 ± 0.04	12	−2.64 ± 0.13	12
May 29 2018	G-9	−26.71 ± 0.16	9	−2.67 ± 0.14	10
May 30 2018	G-9	−26.81 ± 0.11	11	−2.60 ± 0.07	10
May 31 2018	G-9	−26.88 ± 0.28	11	−2.58 ± 0.14	13
June 1 2018	G-9	−26.75 ± 0.19	7	−2.76 ± 0.12	7
Jan 30 2019	G-9	−26.74 ± 0.15	7	−2.43 ± 0.12	7
May 28 2018	USGS-62	−14.79 ± 0.04	6	+20.17 ± 0.07	6
May 29 2018	USGS-62	−14.79 ± 0.06	6	+20.17 ± 0.06	6
May 30 2018	USGS-62	−14.79 ± 0.11	6	+20.17 ± 0.04	6
May 31 2018	USGS-62	−14.79 ± 0.18	6	+20.17 ± 0.06	6
June 1 2018	USGS-62	−14.79 ± 0.2	5	+20.17 ± 0.02	5
Jan 30 2019	USGS-62	−14.79 ± 0.11	7	+20.17 ± 0.12	6
Jan 30 2019	G-32	−28.99 ± 0.16	6	−3.58 ± 0.10	6
Jan 30 2019	IAEA-N-2		0	+20.3	1

repeated measurements of standards and samples, analytical precision ($u(R_w)$) was ±0.17 ‰ for δ^{13}C and ±0.13 ‰ for δ^{15}N. Considering both analytical precision and accuracy, the total standard uncertainty of the samples (u_c) was ±0.28 ‰ for δ^{13}C and ±0.24 ‰ for δ^{15}N.

Table C.3: Stable carbon and nitrogen isotopic compositions for all samples analyzed in triplicate by the Stable Isotope Lab (MUN).

Session	Sample ID	δ^{13}C (VPDB, ‰)	δ^{15}N (AIR, ‰)
May 28 2019	4267	−12.68	+9.63
		−12.70	+9.40
		−12.71	+9.73
May 29 2018	4302	−20.30	+6.39
		−20.39	+6.45
		−20.35	+6.38
May 30 2018	4161	−22.19	+4.40
		−22.19	+4.46
		−22.17	+4.37
May 31 2018	4186	−22.05	+4.10
		−22.02	+4.03
		−21.99	+3.93
June 1 2018	4331	−21.34	+4.61
		−21.31	+4.71
		−21.40	+4.44
Jan 30 2019	4497	−14.01	+10.04
		−14.43	+9.86
		−14.04	+10.21

C.2.2 Ján Veizer Stable Isotope Laboratory, University of Ottawa

Stable carbon and nitrogen isotopic and elemental compositions of nine Caledonia samples prepared without (2516, 2518, 2522, 2530 to 2533, 2535, and 2536) and 14 with (2516B, 2518B, 2519B, 2523B, 2525B, and 2527B to 2535B) a NaOH treatment, as well as samples from Vista Alegre (n = 19), Oxtankah (n = 8), Ichpaatun (n = 2), San Miguelito (n = 2), San Lorenzo (n = 4), Xunantunich (n = 12), San Bernabé (n = 10), Tayasal (n = 5), Caracol (n = 2), Chac II (n = 3), and Calakmul (n = 2) were determined by the Ján Veizer Stable Isotope Laboratory at the University of Ottawa (Appendix A). Stable carbon isotope compositions were normalized to internal standards calibrated to international standards IAEA-CH-6, NBS-22, USGS-40, and USGS-41 relative to VPDB (δ^{13}C). Stable nitrogen

isotope compositions were also normalized to internal standards and calibrated to international standards USGS-40 and USGS-41, as well as IAEA-N1 and IAEA-N2 relative to AIR (δ^{15}N) (Table C.4; Paul Middlestead, personal communication, 2019).

The internal standards listed in Table C.4 were used to monitor analytical uncertainty (Paul Middlestead, personal communication 2019). Excluding C-55, the means and standard deviations of the δ^{13}C and δ^{15}N values for the check and calibration standards as well as the number of standards included in each analytical session were not provided by the lab. Thus, the calculation of analytical uncertainty was based only on the internal standard C-55 (Table C.5) provided by the lab, which was not used for calibration (Paul Middlestead, personal communication 2019). Measurement precision was ±0.04 ‰ for δ^{13}C (df = 3) and ±0.06 ‰ for δ^{15}N (df = 3) and measurement accuracy was ±0.07 ‰ for δ^{13}C ±0.02 ‰ for δ^{15}N.

The carbon and nitrogen isotope compositions of ten bone samples were run in duplicate, the results of which are presented in Table C.6. Although it is unknown whether duplicate analyses were run during the same analytical sessions, it is assumed this will have

Table C.4: Standard reference materials used for calibration of δ^{13}C relative to VPDB and δ^{15}N relative to AIR and to monitor (check) internal accuracy and precision by the Ján Veizer Lab (University of Ottawa).

Standard	Material	Type	Accepted δ^{13}C (‰, VPDB)	Accepted δ^{15}N (‰, AIR)
IAEA-N1	Ammonium sulfate	Calibration	-	+0.4
IAEA-N2	Ammonium sulfate	Calibration	-	+20.3
IAEA-CH6	Sucrose	Calibration	–10.4	-
NBS-22	Oil	Calibration	–29.91	-
USGS-40	L-glutamic acid	Calibration	–26.24	–4.52
USGS-41	L-glutamic acid	Calibration	+37.76	+47.57
C-51	Nicotiamide	Check	–22.95	+0.07
C-52	Ammonium sulfate + sucrose	Check	–11.94	+16.58
C-54	Caffeine	Check	–34.46	–16.61
C-55	Glutamic acid	Check	–28.53	–3.98

Table C.5: Mean and standard deviation of the check standard included in an unknown number of carbon and nitrogen analytical sessions at the Ján Veizer Lab (University of Ottawa).

Session	Standard	N	δ^{13}C (‰, VPDB)	δ^{15}N (‰, AIR)
Unknown	C-55	4	–28.6 ± 0.04	–4.0 ± 0.06

Table C.6: Stable carbon and nitrogen isotopic compositions for all samples analyzed in duplicate by the Ján Veizer Lab (University of Ottawa).

Sample ID	δ^{13}C (VPDB, ‰)	δ^{15}N (AIR, ‰)
2519B	−11.74	+11.65
	−11.80	+11.58
2523B	−8.38	+10.47
	−8.54	+10.56
2532B	−8.62	+9.20
	−8.66	+9.24
4406	−7.87	+9.23
	−7.85	+9.16
4564	−20.48	+3.92
	−20.48	+3.88
4574	−9.24	+10.12
	−9.14	+10.11
4585	−21.40	+4.69
	−21.43	+4.71
4592	−9.46	+8.79
	−9.50	+8.76
4757	−9.65	+9.95
	−9.61	+9.82
4924	−10.86	+8.09
	−10.45	+8.25

no influence on the results. The measurement precision specific to the samples was ±0.10 ‰ for δ^{13}C and ±0.06 ‰ for δ^{15}N (df = 10).

Measurement precision was calculated using a single check standard (C-55) and was ±0.08 ‰ for δ^{13}C and ±0.07 ‰ for δ^{15}N. Finally, considering both analytical precision and accuracy, the total standard uncertainty for the analyses conducted at the Ján Veizer Stable Isotope Laboratory was ±0.11 ‰ for δ^{13}C and ±0.08 ‰ for δ^{15}N.

C.3 Sulfur Isotope Analysis of Bone Collagen

C.3.1 Stable Isotope Laboratory, Memorial University of Newfoundland

Stable sulfur isotopic and elemental compositions of 20 samples from Caledonia prepared without a NaOH treatment (Lab #s 2514 to 2523, and 2525 to 2536) were analyzed at the MUN SIL. Stable sulfur isotope compositions were calibrated relative to IAEA-S-1 and IAEA-S-2 (Table C.7). The internal standards listed in Table C.7 were used to monitor analytical uncertainty. Their isotopic compositions represent long term averages calibrated to VCDT with IAEA-S-1 and IAEA-S-2 (Alison Pye, personal communication 2018). The means and standard deviations of the δ^{34}S values for the calibration standards as well as the number of standards included in each analytical session are presented in Table C.8. Based on the calibration and check standards, measurement precision was ±0.45 ‰ for δ^{34}S (df = 36) and measurement accuracy was ±0.86 ‰ for δ^{34}S.

The 10 samples listed in Table C.9 were run in duplicate. The duplicates of each

Table C.7: Standard reference materials used for calibration of δ^{34}S relative to VCDT and to monitor (check) internal accuracy and precision by the Stable Isotope Lab (MUN).

Standard	Type	Material	Accepted δ^{34}S (‰, VCDT)
IAEA-S-1	Calibration	Silver sulfide	–0.3
IAEA-S-2	Calibration	Silver sulfide	+22.67 ± 0.15
NBS-127	Check	Barium sulfate	+21.1 ± 0.36
G-50	Check	Protein B2155 (casein)	+6.57 ± 0.8

Table C.8: Mean and standard deviation of all check and calibration standards for all sulfur analytical sessions at the Stable Isotope Lab (MUN).

Session	Standard	N	δ^{34}S (‰, VCDT)
Sept 4 2015	IAEA-S-1	7	–0.30 ± 0.30
Sept 9 2015	IAEA-S-1	7	–0.36 ± 0.27
Sept 4 2015	IAEA-S-2	9	+22.67 ± 0.08
Sept 9 2015	IAEA-S-2	9	+22.67 ± 0.22
Sept 4 2015	NBS-127	4	+21.67 ± 1.19
Sept 9 2015	NBS-127	4	+21.85 ± 0.63
Sept 4 2015	G-50	2	+7.04 ± 0.06
Sept 9 2015	G-50	2	+5.99 ± 0.18

Table C.9: Stable sulfur isotopic compositions for all samples analyzed in duplicate by the Stable Isotope Lab (MUN).

Sample ID	δ^{34}S (VCDT, ‰)	
	Sept. 4, 2015	Sept. 9, 2015
2514	+10.27	+9.00
2515	+12.43	+13.59
2516	+10.14	+12.89
2517	+11.73	+14.13
2518	+12.25	+11.01
2519	+10.74	+9.67
2521	+12.93	+11.09
2523	+12.69	+12.66
2528	+13.73	+13.73
2532		+13.13 +14.21

sample except 2532 were run in different sessions; however, their values were not statistically different (see Appendix B), and so they were included in the calculation of measurement precision specific to the samples, which was ±1.08 ‰ for δ^{34}S (df = 10). Based on the pooled standard deviations of all repeated measurements of standards and samples, analytical precision was ±0.89 ‰ for δ^{34}S and the total standard uncertainty (u_c) was ±1.24 ‰ for δ^{34}S.

C.3.2 Stable Isotope Laboratory, University of Tennessee Knoxville

Stable sulfur isotopic and elemental compositions of samples from Caledonia prepared without (n = 8) and with (n = 9) a NaOH step, as well as samples from Pacbitun (n = 31), Moho Cay (n = 1), Laguna de On Island (n = 42), Laguna de On Shore (n = 1), Caye Coco (n = 27), Chanlacan (n = 18), Caye Muerto (n = 1), Nakum (n = 22), Vista Alegre (n = 18), Oxtankah (n = 7), Ichpaatun (n = 2), and San Miguelito (n = 2) were analyzed in the Stable Isotope Laboratory at the University of Tennessee Knoxville. Stable

sulfur isotope compositions were calibrated relative to NBS-127 and IAEA-SO-6 (Table C.10; Anthony Faiia, personal communication, 2018).

The means and standard deviations of the $\delta^{34}S$ values for the calibration standards and the number of standards included in each analytical session are presented in Table C.11. Based on the calibration standards, measurement precision was ±0.74 ‰ for $\delta^{34}S$ ($df = 69$). Measurement accuracy could not be calculated because check standards were not included in the analyses.

Twenty-eight samples were run in duplicate and two were run in triplicate (Table C.12). All duplicates or triplicates were analyzed in different sessions, excluding 4161 and 4192, the duplicates of which were both run on Nov. 30, 2018. However, differences in the $\delta^{34}S$ and wt. %S of sample duplicates run during separate analytical sessions was found to

Table C.10: Standard reference materials used for calibration of $\delta^{34}S$ relative to VCDT at the Stable Isotope Lab (University of Tennessee Knoxville).

Standard	Material	Accepted $\delta^{34}S$ (‰, VCDT)
NBS-127	Barium Sulfate	+20.30 ± 0.40
IAEA-SO-6	Barium Sulfate	–34.10 ± 0.20

Table C.11: Mean and standard deviation of all calibration standards for all sulfur analytical sessions at the Stable Isotope Lab (University of Tennessee Knoxville).

Session	Standard	N	$\delta^{34}S$ (‰, VCDT)
Nov. 8, 2018	IAEA-SO-2	3	–34.05 ± 0.06
Nov. 14, 2018	IAEA-SO-2	8	–34.05 ± 1.5
Nov. 25, 2018	IAEA-SO-2	6	–33.89 ± 0.52
Nov. 26, 2018	IAEA-SO-2	6	–34.05 ± 0.41
Nov. 27, 2018	IAEA-SO-2	6	–34.05 ± 0.99
Nov. 28, 2018	IAEA-SO-2	8	–34.05 ± 0.80
Nov. 30, 2018	IAEA-SO-2	7	–33.75 ± 0.93
Nov. 8, 2018	NBS-127	2	+21.12 ± 0.12
Nov. 14, 2018	NBS-127	7	+21.15 ± 0.26
Nov. 25, 2018	NBS-127	6	+21.12 ± 0.33
Nov. 26, 2018	NBS-127	5	+21.12 ± 0.26
Nov. 27, 2018	NBS-127	5	+21.12 ± 0.35
Nov. 28, 2018	NBS-127	8	+21.12 ± 0.65
Nov. 30, 2018	NBS-127	6	+21.12 ± 0.40

Table C.12: Stable sulfur isotopic compositions for all samples analyzed in duplicate or triplicate at the Stable Isotope Lab (University of Tennessee Knoxville).

Sample ID	δ^{34}S (VCDT, ‰)		
	Session 1	Session 2	Session 3
2558	+11.82	+11.08	
2561	+13.42	+13.17	
3451	+16.71	+14.20	
3458	+13.30	+13.22	
4155	+14.66	+13.67	
4161	+8.23	+8.99	
4192	+4.43	+4.69	
4255	+13.05	+11.90	
4260	+11.41	+13.39	
4261	+9.61	+9.44	
4262	+13.28	+13.38	+12.30
4263	+12.70	+12.92	
4267	+8.81	+8.23	
4268	+10.94	+10.54	
4270	+12.48	+11.97	+11.73
4271	+14.24	+13.79	
4272	+13.72	+10.71	
4273	+12.66	+12.01	
4274	+17.13	+17.12	
4294	+14.18	+13.27	
4303	+14.12	+13.53	
4305	+9.38	+6.77	
4320	+13.40	+12.03	
4328	+14.40	+13.47	
4332	+14.02	+13.06	
4406	+11.75	+11.42	
4522	-0.18	-2.34	
4533	+13.14	+12.14	
4553	-1.14	-4.47	
4555	+13.24	+11.27	

Note: Sessions 1, 2, and 3, are specific to each sample, as not every sample was run during each analytical session.

be statistically insignificant (see Appendix B), and so they were included in the calculation of measurement precision specific to the samples, which was ±0.96 ‰ for δ^{34}S (df = 32).

Based on the pooled standard deviations of all repeated measurements of the calibration standards and samples, analytical precision was ±1.00 ‰ for δ^{34}S. However, because analytical accuracy could not be calculated, neither could the standard uncertainty.

C.3.3 Ján Veizer Stable Isotope Laboratory, University of Ottawa

Stable sulfur isotopic and elemental compositions of samples from Caledonia (n=1), Xunantunich (n = 7), San Lorenzo (n = 1), San Bernabé (n = 8), and Calakmul (n = 1) were analyzed by the Ján Veizer Stable Isotope Laboratory, University of Ottawa. The values and number of standards used to calibrate the δ^{34}S values were not provided by the lab, although analytical precision was stated to be ±0.2 ‰ (Paul Middlestead, personal communication, 2019). The internal standards listed in Table C.13 were used to monitor analytical uncertainty (Paul Middlestead, personal communication, 2019).

The means and standard deviations of the δ^{34}S values for the check standards and the number of standards included in each analytical session are presented in Table C.14. Because the data from the calibration standards were not provided, measurement precision was based only on the check standards and was ±0.13 ‰ (df = 4). Measurement accuracy was ±0.29 ‰ for δ^{34}S.

Unfortunately, due to the large amount of sample (55 mg) required for analysis, none of the samples were run in duplicate. As a result, analytical precision was based only

Table C.13: Standard reference materials used to monitor (check) internal accuracy and precision at the Ján Veizer Lab (University of Ottawa).

Standard	N	Material	Mean δ^{34}S (‰, VCDT)
S-6	5	AG-2	–0.71
S-13131	1	Egg	+3.51
S-13132	1	DCO Liver	+4.66
S-13133	1	Nova Egg	+17.59

Table C.14: Mean and standard deviation of all check standards for all sulfur analytical sessions at the Ján Veizer Lab (University of Ottawa).

Standard	N	δ^{34}S (‰, VCDT)
S-6	5	–0.72±0.13
S-13131	1	+2.95
S-13132	1	+4.57
S-13133	1	+17.63

on the check standards and was therefore the same as the measurement precision (±0.13 ‰) for δ^{34}S. Based on analytical accuracy and precision, the standard uncertainty was ±0.32 ‰ for δ^{34}S.

C.4 Calibration and Analytical Uncertainty of the Nakum Isotopic Measurements

Because the Nakum case study presented in the Chapter 5 was published prior to the other chapters, the calibration and analytical uncertainty of the stable isotopic results were calculated using the Szpak et al. (2017a) method only for the Nakum samples in Rand and colleagues (2020a). These data are presented below and because they are site-specific, they differ slightly from those for each laboratory and isotope system presented above.

C.4.1 Carbon and Nitrogen Isotope Analysis of the Nakum Bone Collagen Samples

Stable carbon and nitrogen isotopic and elemental compositions were determined using a Thermo Scientific Delta V-Plus I Gas Source isotope ratio mass spectrometer (IRMS) coupled to a Carlo Erba NA 1500 Series II elemental analyzer in the Stable Isotope Laboratory (Memorial University of Newfoundland). Stable carbon and nitrogen isotope compositions were calibrated relative to VPDB (δ^{13}C) and AIR (δ^{15}N) using EDTA #2, USGS62, and IAEA-N-2 (Table C.15). The internal standards listed in Table C.16 were

Table C.15: Standard reference materials used for calibration of δ^{13}C relative to VPDB and δ^{15}N relative to AIR during analysis of the Nakum bone collagen samples.

Standard	Material	Accepted δ^{13}C (‰, VPDB)	Accepted δ^{15}N (‰, AIR)
EDTA #2	EDTA	–40.38 ± 0.01	–0.83 ± 0.04
USGS-62	Caffeine	–14.79 ± 0.04	+20.17 ± 0.06
IAEA-N-2	Ammonium sulfate		+20.32 ± 0.09

used to monitor analytical uncertainty. Their isotopic compositions represent long term averages calibrated to VPDB and AIR with USGS62 and EDTA #2 (Alison Pye, personal communication 2018).

The means and standard deviations of the $\delta^{13}C$ and $\delta^{15}N$ values for the check and calibration standards as well as the number of standards included in each analytical session are presented in Table C.17. Based on the check and calibration standards, measurement precision (the pooled standard deviation of the check and calibration standards) was ±0.17

Table C.16: Standard reference materials used to monitor internal accuracy and precision for all carbon and nitrogen isotope values of the Nakum bone collagen samples.

Standard	Material	Mean $\delta^{13}C$ (‰, VPDB)	Mean $\delta^{15}N$ (‰, AIR)
G-9	L-glutamic acid	–26.74±0.06	–2.77±0.18
G-32	Sulfanilamide	–28.96±0.22	–3.62±0.25
G-40	B2155 (protein)	–27.03±0.13	+5.97±0.08

Table C.17: Mean and standard deviation of all check and calibration standards for all carbon and nitrogen analytical sessions.

Session	Standard	N	$\delta^{13}C$ (‰, VPDB)	$\delta^{15}N$ (‰, AIR)
Human C & N	EDTA	6	–40.38±0.16	–0.83±0.03
Fauna C & N 1	EDTA	6	–40.38±0.16	–0.83±0.09
Fauna C & N 2	EDTA	5	–40.38±0.19	–0.83±0.05
Fauna C & N 3	EDTA	6	–40.38±0.02	–0.83±0.06
Human C & N	USGS-62	7	–14.79±0.11	20.17±0.12
Fauna C & N 1	USGS-62	6	–14.79±0.18	+20.17±0.05
Fauna C & N 2	USGS-62	5	–14.79±0.20	+20.17±0.02
Fauna C & N 3	USGS-62	6	–14.79±0.06	+20.17±0.06
Human C & N	IAEA-N-2	1		+20.3
Human C & N	G-9	7	–26.74±0.15	–2.43±0.12
Fauna C & N 1	G-9	11	–26.88±0.21	–2.58±0.13
Fauna C & N 2	G-9	10	–26.75±0.17	–2.79±0.14
Fauna C & N 3	G-9	10	–26.71±0.16	–2.67±0.14
Human C & N	G-32	6	–28.99±0.16	–3.58±0.10
Human C & N	G-40	6	–27.24±0.18	+6.09±0.08
Fauna C & N 1	G-40	4	–27.27±0.22	+5.95±0.08
Fauna C & N 2	G-40	3	–27.34±0.16	+5.98±0.11
Fauna C & N 3	G-40	4	–27.24±0.04	+5.9±0.10

Please note Fauna C & N Session 1 includes MARCs 4322, 4326, 4327, and 4330, Fauna C & N Session 2 includes MARCs 4317, 4319, 4320, 4325, 4328, 4329, 4331, 4332), and Fauna C & N Session 3 includes MARCs 4315, 4318, 4323, and 4324.

‰ for $\delta^{13}C$ (df = 91) and ±0.12 ‰ for $\delta^{15}N$ (df = 89). Measurement accuracy (bias) was evaluated by comparing the known and measured $\delta^{13}C$ and $\delta^{15}N$ values for G-9, G-32 and G-40 and factoring in the long-term uncertainty in these known measurements following Szpak et al. (2017). Measurement bias due to systematic error (accuracy) was determined to be ±0.21 ‰ for $\delta^{13}C$ and ±0.20 ‰ for $\delta^{15}N$.

The carbon and nitrogen isotope compositions of one human and one fauna bone sample were run in triplicate, the results of which are presented in Table C.18. The measurement precision specific to the samples (the pooled standard deviation of all samples analyzed in triplicate) was ±0.17‰ for $\delta^{13}C$ and ±0.16‰ for $\delta^{15}N$ (df=4).

C.4.2 Sulfur Isotope Analysis of the Nakum Bone Collagen Samples

Stable sulfur isotopic and elemental compositions were determined using a Thermo Scientific Delta Plus IRMS coupled to a Costech EA (ECS4010) in the Stable Isotope Laboratory (University of Tennessee). Stable sulfur isotope compositions were calibrated relative to VCDT using NBS-127 and IAEA-SO-6 (Table C.19).

Table C.18: Stable carbon and nitrogen isotopic compositions for all Nakum bone collagen samples analyzed in duplicate.

Sample ID	$\delta^{13}C_A$ (VDPB, ‰)	$\delta^{13}C_B$ (VDPB, ‰)	$\delta^{13}C_C$ (VDPB, ‰)	$\delta^{15}N_A$ (AIR, ‰)	$\delta^{15}N_B$ (AIR, ‰)	$\delta^{15}N_C$ (AIR, ‰)
4331	–21.34	–21.31	–21.4	+4.61	+4.71	+4.44
4497	–14.01	–14.43	–14.04	+10.04	+9.86	+10.21

Table C.19: Standard reference materials used for calibration of $\delta^{34}S$ relative to VCDT during analysis of the Nakum bone collagen samples.

Standard	Material	Accepted $\delta^{34}S$ (‰, VCDT)	$\delta^{34}S$ (‰, VCDT) used by Lab to Correct Values*
NBS-127	Barium sulfate	+20.3 ± 0.4	+21.12
IAEA-SO-6	Barium sulfate	–34.1 ± 0.2	–34.05

*Data provided by Anthony Fiia (personal communication, 2018).

The means and standard deviations of the $\delta^{34}S$ values for the calibration standards as well as the number of standards included in each analytical session are presented in Table C.20. Based on the calibration standards, measurement precision (the pooled standard deviation of the calibration standards) was ±0.84 ‰ for $\delta^{34}S$ (df = 33). It was not possible to analyze measurement accuracy, as no internal standards were included in the analysis.

The sulfur isotope compositions of three faunal bone samples were run in duplicate, the results of which are presented in Table C.21. The measurement precision specific to the samples (the pooled standard deviation of all samples analyzed in duplicate) was ±0.78‰ for $\delta^{34}S$ (df=3). This value is quite large and may be so because the duplicates were analyzed on different days.

Table C.20: Mean and standard deviation of all check and calibration standards for all sulfur analytical sessions of the Nakum bone collagen samples.

Session	Standard	N	$\delta^{34}S$ (‰, VCDT)
Session 1	NBS-127	5	+21.12 ± 0.26
Session 2	NBS-127	7	+21.15 ± 0.26
Session 3	NBS-127	6	+21.12 ± 0.40
Session 1	IAEA-SO-6	6	–34.05 ± 0.41
Session 2	IAEA-SO-6	8	–34.05 ± 1.50
Session 3	IAEA-SO-6	7	–33.74 ± 0.93

Please note Session 1 includes MARCs 4331, 4332, 4497, 4498, 4500, 4507, and 4511, Session 2 includes MARCs 4315, 4317 to 4320, and 4322 to 4330, and Session 3 includes MARC 4316 and duplicate analyses of MARCS 4320, 4328, and 4332.

Table C.21: Stable sulfur isotopic compositions for all Nakum bone collagen samples analyzed in duplicate.

Sample ID	$\delta^{34}S_A$ (VCDT, ‰)	$\delta^{34}S_B$ (VCDT, ‰)
4320	+13.4	+12.0
4328	+14.4	+13.5
4322	+14.0	+13.1

Note: A refers to the first run (Session 1 or 2) and B refers to the duplicate analysis during Session 3.

C.4.3 Oxygen and Carbon Isotope Analysis of the Nakum Bone and Tooth Enamel Bioapatite Samples

Stable oxygen and carbon isotopic compositions were analyzed by the SIL at MUN. Stable carbon and oxygen compositions were calibrated relative to VPDB using NBS-19 (Table C.22). The internal standards listed in Table C.22 were used to monitor analytical uncertainty. Their isotopic compositions represent long term averages calibrated to VPDB using NBS-19 (Alison Pye, personal communication 2018).

The means and standard deviations of the $\delta^{13}C$ and $\delta^{18}O$ values for the check and calibration standards as well as the number of standards included in each analytical session are presented in Table C.23. Based on the check and calibration standards, measurement precision was ±0.04 ‰ for $\delta^{13}C$ (df = 15) and ±0.07 ‰ for $\delta^{18}O$ (df = 14). Measurement accuracy was ±0.08 ‰ for $\delta^{13}C$ and ±0.09 ‰ for $\delta^{18}O$. The carbon and oxygen isotope compositions of one human bone (4511) and one tooth (4515) sample were run in triplicate, the results of which are presented in Table C.24. The measurement precision specific to the samples was ±0.22 ‰ for $\delta^{13}C$ and ±0.42 ‰ for $\delta^{18}O$ (df = 4). Based on the pooled standard deviations of all repeated measurements of standards and samples, analytical precision was 0.16 ‰ for $\delta^{13}C$ and 0.31 ‰ for $\delta^{18}O$. The overall standard uncertainty was ±0.18 ‰ for $\delta^{13}C$ and ±0.32 ‰ for $\delta^{18}O$.

Table C.22: Standard reference materials used for calibration of $\delta^{13}C$ and $\delta^{18}O$ relative to VPDB and to monitor (check) internal accuracy and precision by the SIL at MUN during analysis of the Nakum samples.

Standard	Material	Type	$\delta^{18}O$ (VPDB, ‰)	$\delta^{18}O$ (VSMOW, ‰)	$\delta^{13}C$ (VDPB, ‰)
NBS-19	$CaCO_3$	Calibration	–2.20	+28.65	+1.95
C-5	CBM ($CaCO_3$)	Check	(–8.58)	+22.07 ± 0.1	+0.75 ± 0.06
C-132	MUN-CO-1 ($CaCO_3$)	Check	–13.40 ± 0.12	(+17.10)	–21.02 ± 0.10

Table C.23: Mean and standard deviation of all check and calibration standards for carbon and oxygen analytical sessions for the Nakum samples.

Standard	N	$\delta^{18}O$ (‰, VPDB)	$\delta^{13}C$ (‰, VPDB)
NBS-19	6	–2.20 ± 0.04	+1.95 ± 0.03
C-5	6	–8.6 ± 0.11	+0.75 ± 0.05
C-132	6	–13.40 ± 0.03	–21.02 ± 0.04

Table C.24: Stable carbon and oxygen isotopic compositions for all Nakum samples analyzed in duplicate.

Sample ID	$\delta^{13}C_A$ (VDPB, ‰)	$\delta^{13}C_B$ (VDPB, ‰)	$\delta^{13}C_C$ (VDPB, ‰)	$\delta^{18}O_A$ (VDPB, ‰)	$\delta^{18}O_B$ (VDPB, ‰)	$\delta^{18}O_C$ (VDPB, ‰)
4511	-6.02	-6.12	–6.17	–4.87	–4.41	–4.46
4515	-3.19	-3.61	–3.01	–4.00	–4.63	–3.56

C.6 Discussion and Conclusion

The measurements of analytical uncertainty discussed in detail above are summarized in Table C.25. Unfortunately, check standards were not included in the Tennessee analyses and sample replicates were not analyzed at Ottawa, nor did this lab provide the data from the calibration standards. This complicates the comparison of the analytical uncertainties among laboratories, and so only analytical accuracy and/or precision are considered in the following comparison.

The $\delta^{13}C$ and $\delta^{15}N$ values analyzed at Ottawa are substantially more accurate than those from MUN. This is likely because the former lab provided the information for only a single standard reference material, whereas all data was available from the latter lab.

In terms of $\delta^{34}S$ values, the measurements made at MUN were more precise than those from Tennessee, but both had a comparably wide range. While it appears as though Ottawa had the most accurate and precise measurements of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values compared to MUN and Tennessee, this is likely because the calculations were based on

Table C.25 Measurements of analytical uncertainty for each isotope measurement by laboratory.

Isotope Measurement	Laboratory	Measurement Precision			Precision specific to the samples (s_{rep})	Analytical precision ($u(R_w)$)	Analytical accuracy ($u(bias)$)	Standard uncertainty (u_c)
		Calibration Standards Only	Check Standards Only	Check and Calibration Standards (s_{srm})				
$\delta^{13}C_{col}$	MUN	±0.13‰	±0.12‰	±0.15‰	±0.10‰	±0.17‰	±0.23‰	±0.28‰
	Ottawa	N/A	±0.04‰	±0.04‰	±0.10‰	±0.08‰	±0.07‰	±0.11‰
$\delta^{15}N$	MUN	±0.06‰	±0.12‰	±0.10‰	±0.12‰	±0.13‰	±0.20‰	±0.24‰
	Ottawa	N/A	±0.06‰	±0.06‰	±0.06‰	±0.07‰	±0.02‰	±0.08‰
$\delta^{34}S$	MUN	±0.25‰	±0.83‰	±0.45‰	±1.08‰	±0.89‰	±0.86‰	±1.24‰
	Tennessee*	±0.74‰	N/A	±0.74‰	±0.96‰	±1.00‰	N/A	N/A
	Ottawa	±0.20‰**	±0.13‰	±0.13‰	N/A	±0.13‰	±0.29‰	±0.32‰
$\delta^{13}C_{ap}$	MUN	±0.02‰	±0.04‰	±0.04‰	±0.22‰	±0.16‰	±0.08‰	±0.18‰
$\delta^{18}O$	MUN	±0.02‰	±0.07‰	±0.07‰	±0.42‰	±0.31‰	±0.09‰	±0.32‰

Note: Subscript col = collagen and ap = apatite.

*Analytical accuracy and therefore standard uncertainty could not be calculated for the Tennessee data because check standards were not included in the analyses.

**Value provided by the lab but not included in calculation of analytical uncertainty.

limited data. Specifically, the calculation of analytical uncertainty for the $\delta^{13}C$ and $\delta^{15}N$ values from Ottawa were based on 10 replicate samples, but the mean and standard deviation of only a single check standard were provided by the lab. Similarly, the calculation of analytical uncertainty for $\delta^{34}S$ values from Ottawa was based on the means and standard deviations of four check standards provided by the lab rather than the individual values of these standards obtain in each run and no calibration standards or sample replicates were included in these calculations. The overall lack of information about the standard reference materials included in the analytical sessions therefore make it difficult to comprehensively evaluate the analytical uncertainty associated with the isotopic measurements made at Ottawa.

The analytical uncertainty associated with $\delta^{34}S$ values is higher than those of $\delta^{13}C$, $\delta^{15}N$, and $\delta^{18}O$ values (Table C.25). Other archaeological studies that have analyzed sulfur isotopes also found elevated levels of uncertainty, although the analytical precision of the $\delta^{34}S$ analyzed by MUN (±0.89 ‰) and Tennessee (±1.00 ‰) are much broader than those reported in other studies which range from ±0.20 to ±0.60 ‰ (Craig et al. 2006; Fornander et al. 2008; Linderholm et al. 2008b; Nehlich et al. 2010; Privat et al. 2007; Richards et al. 2001, 2003; Sayle et al. 2013). This is likely because precision reported in other studies is based on the measurement precision of the calibration standards analyzed with the samples, whereas analytical precision calculated using the method of Szpak et al. (2017a) includes the variability of the calibration standards as well as check standards and sample replicates. When the measurement precisions of only the calibration standards are considered, the "precision" of the MUN (±0.22 ‰) and Ottawa (±0.20 ‰) analyses are comparable with the values reported in other studies (Table C.25). This indicates that the exclusion of the

variability of additional standards as well as sample replicates from the calculation of analytical uncertainty superficially increases precision.

To investigate this further, the sample replicates were removed from the calculation of analytical precision for the MUN and Tennessee analyses. As a result, the precision of the MUN analyses improved from ±0.89 to ±0.45 ‰ as did that of the Tennessee analyses from ±1.00 to ±0.74 ‰. As has been observed elsewhere (Jardine and Cunjak 2005), this demonstrates that although the inclusion of sample replicates in the calculation of analytical precision appears to be less precise, it is in reality more robust in terms of reflecting the true uncertainty in the isotopic values obtained from heterogeneous sample materials such as bone collagen. Researchers should therefore request the necessary data from the laboratories at which their data is generated and use a standardized method to calculate analytical uncertainty (e.g., Szpak et al. 2017a) to ensure comparability among studies.

As researchers are becoming more aware that differing preparation and analytical methods can influence the comparability of isotopic data sets (Chesson et al. 2019; Pestle et al. 2014), it is also important to provide comparable measures of the analytical uncertainty associated with the analyses, as has been proposed by Szpak et al. (2017a). However, since the guidelines by Szpak and colleagues (2017a) were published, few archaeological isotope studies have reported analytical uncertainty using their methodology. Furthermore, most studies that did use this method primarily examined archaeological plants (Metcalfe and Mead 2019; Vaiglova 2020) or animals (Fuller et al. 2020; Guiry et al. 2020; Harris et al. 2020; Szpak and Valenzuela 2020), and rarely humans (but see Munkittrick et al. 2019). Other studies utilized the methodology proposed by Szpak et al. (2017a) but reported measurement precision and analytical accuracy rather than the

overall analytical uncertainty for consistency with earlier studies (Clark et al. 2019; Rand et al. 2020a). Future utilization of the standardized analytical uncertainty proposed by Szpak et al. (2017a) will increase the comparability of isotopic data produced by different labs using different techniques.

APPENDIX D

SPECIES, CONTEXTUAL, AND ISOTOPIC DATA OF THE MAYA FAUNAL SAMPLES

Table D.1: Contextual and species data for the Maya faunal samples.

Lab #	Site	Common Name	Scientific Name	Time Period	Context	Age	Skeletal Element
2575	Pacbitun	Deer	Cervidae	PreC	4:328	A	Fragment
3443	Pacbitun	White-tailed deer	*Odocoileus virginianus*	C	1:283:1	A	Tibia
3444	Pacbitun	White-tailed deer	*Odocoileus virginianus*	C	4:155:1	A	Fragment
3445	Pacbitun	White-tailed deer	*Odocoileus virginianus*	C	38:202:7	A	Femur
3446	Pacbitun	White-tailed deer	*Odocoileus virginianus*	C	38:238:3	A	Ulna
3447	Pacbitun	White-tailed deer	*Odocoileus virginianus*	C	38:244:1	A	Fragment
3448	Pacbitun	Brocket deer	*Mazama* sp.	C	15:236:6	A	Fragment
3449	Pacbitun	Brocket deer	*Mazama* sp.	LPreC	23:104:23	A	Metapodial
3450	Pacbitun	Lowland paca	*Cuniculus paca*	C	1:3:1	A	Tibia
3451	Pacbitun	Lowland paca	*Cuniculus paca*	C	23:102:1	A	Fragment
3452	Pacbitun	Lowland paca	*Cuniculus paca*	C	15:236:1	A	Fragment
3453	Pacbitun	Agouti	*Dasyprocta* sp.	LPreC	23:103:4	A	Ulna
3454	Pacbitun	Peccary	Tayassuidae	C	2:16:1	A	Fragment
3455	Pacbitun	White-lipped peccary	*Tayassu pecari*	LPreC	23:103:2	A	Fragment
3456	Pacbitun	Turkey	*Meleagris* sp.	C	2:18:4	A	Fragment
3457	Pacbitun	Feline	Felidae	C	2:34:B2-3	A	Proximal Phalanx
3458	Pacbitun	Turtle	Testudines	C	2:55:1	A	Fragment
3459	Pacbitun	Turtle	Testudines	C	4:12:24	A	Fragment
3460	Pacbitun	Turtle	Kinosternidae	C	4:212:16	A	Fragment
3461	Pacbitun	Turtle	Kinosternidae	C	15:236:11	A	Fragment
3462	Moho Cay	Caribbean manatee	*Trichechus manatus manatus*	E-LC	95	A	Rib
4150	Laguna de On Island	Weasel	Mustelidae	E-LPC	2:2	A	L Calcaneus
4152	Laguna de On Island	Opossum	Didelphidae	E-LPC	5:12	A	R Mandible
4153	Laguna de On Island	Wild turkey	*Meleagris gallopavo*	E-LPC	16C:260	A	Ulna
4154	Laguna de On Island	Wild turkey	*Meleagris gallopavo*	E-LPC	5:9	A	Proximal tibiotarsus
4155	Laguna de On Island	Sea turtle	Cheloniidea	E-LPC	17:221	A	Carapace
4157	Laguna de On Island	Dog	*Canis lupus familiaris*	E-LPC	17B:277	A	L Humerus
4159	Laguna de On Island	White-tailed deer	*Odocoileus virginianus*	E-LPC	5D:211	A	L 1st Phalanx
4160	Laguna de On Island	White-tailed deer	*Odocoileus virginianus*	E-LPC	5N:337	A	R 4th Phalanx

Table D.1 Continued.

Lab #	Site	Common Name	Scientific Name	Time Period	Context	Age	Skeletal Element
4161	Laguna de On Island	White-tailed deer	*Odocoileus virginianus*	E-LPC	17:389	A	R Femur
4162	Laguna de On Island	White-tailed deer	*Odocoileus virginianus*	E-LPC	11:1	A	L Innominate
4163	Laguna de On Island	White-tailed deer	*Odocoileus virginianus*	E-LPC	4:5	A	L Calcaneus
4165	Laguna de On Island	White-tailed deer	*Odocoileus virginianus*	E-LPC	2:3	A	R Patella
4166	Laguna de On Island	White-tailed deer	*Odocoileus virginianus*	E-LPC	5:5	A	Metapodial
4168	Laguna de On Island	Peccary	Tayassuidae	E-LPC	8P:380	A	L Femur
4169	Laguna de On Island	White-lipped peccary	*Tayassu pecari*	E-LPC	2:2	A	R Calcaneus
4170	Laguna de On Island	White-lipped peccary	*Tayassu pecari*	E-LPC	2:3	A	Phalanx
4173	Laguna de On Island	Nine-banded armadillo	*Dasypus novemcinctus*	E-LPC	2:3	A	L Calcaneus
4175	Laguna de On Island	Opossum	Didelphidae	E-LPC	17:241	A	L Humerus
4176	Laguna de On Island	Nine-banded armadillo	*Dasypus novemcinctus*	E-LPC	10:1	A	R Femur
4178	Laguna de On Island	Nine-banded armadillo	*Dasypus novemcinctus*	E-LPC	8:1	A	R Femur
4179	Laguna de On Island	Nine-banded armadillo	*Dasypus novemcinctus*	E-LPC	2:2	A	L Calcaneus
4180	Laguna de On Island	Nine-banded armadillo	*Dasypus novemcinctus*	E-LPC	2:2	A	R Calcaneus
4181	Laguna de On Island	Red brocket deer	*Mazama americana*	E-LPC	5:1	A	L 1st Phalanx
4182	Laguna de On Island	Red brocket deer	*Mazama americana*	E-LPC	2:2	A	R Astragalus
4186	Laguna de On Island	Brocket deer	*Mazama* sp.	E-LPC	5J:275	A	L 1st Phalanx
4189	Laguna de On Island	Crocodile	Crocodylidae	E-LPC	10:1	A	L Humerus
4190	Laguna de On Island	Crocodile	Crocodylidae	E-LPC	8:12	A	Cranium
4192	Laguna de On Island	Crocodile	Crocodylidae	E-LPC	8:2	A	Scute
4193	Laguna de On Island	Crocodile	Crocodylidae	E-LPC	8:9	A	Scute

Table D.1 Continued.

Lab #	Site	Common Name	Scientific Name	Time Period	Context	Age	Skeletal Element
4194	Laguna de On Island	Mesoamerican slider	*Trachemys venusta*	E-LPC	5:4	A	Carapace
4195	Laguna de On Island	Mesoamerican slider	*Trachemys venusta*	E-LPC	5:8	A	Carapace
4196	Laguna de On Island	Mesoamerican slider	*Trachemys venusta*	E-LPC	5:3	A	Carapace
4197	Laguna de On Island	Freshwater turtle	Testudines	E-LPC	10:3	A	Carapace
4200	Laguna de On Island	Freshwater turtle	Testudines	E-LPC	10:1	A	Neural
4201	Laguna de On Island	Freshwater turtle	Testudines	E-LPC	2:1	A	Carapace
4202	Laguna de On Island	Freshwater turtle	Testudines	E-LPC	10:2	A	Neural
4203	Laguna de On Island	Freshwater turtle	Testudines	E-LPC	8:2	A	Carapace
4205	Laguna de On Island	Freshwater turtle	Testudines	E-LPC	8:4	A	Carapace
4207	Laguna de On Island	Sea catfish	Ariidae	E-LPC	2:5	A	L Pectoral Spine
4208	Laguna de On Island	Sea catfish	Ariidae	E-LPC	2:2	A	L Pectoral Spine
4210	Laguna de On Island	Sea catfish	Ariidae	E-LPC	8:9	A	R Pectoral Spine
4211	Laguna de On Island	Sea catfish	Ariidae	E-LPC	8:8	A	Cleithrum
4212	Laguna de On Island	Sea catfish	Ariidae	E-LPC	5:4	A	L Cleithrum
4213	Laguna de On Island	Sea catfish	Ariidae	E-LPC	8:12	A	L Cleithrum
4214	Laguna de On Island	Freshwater catfish	Siluriformes	E-LPC	5:5	A	R Pectoral Spine
4215	Laguna de On Island	Freshwater catfish	Siluriformes	E-LPC	2:3	A	Dorsal Spine
4250	Caye Coco	Mojarra	Gerridae	LPC	18B:718	A	R Maxilla
4252	Caye Coco	Crocodile	Crocodylidae	LPC	18B:721	A	R Femur
4253	Caye Coco	Peccary	Tayassuidae	LPC	18:637:4	A	Radius/Ulna
4254	Caye Coco	Peccary	Tayassuidae	LPC	38:1187:5	A	Scapula
4255	Caye Coco	Peccary	Tayassuidae	LPC	38:1181:4	A	Metacarpal
4256	Caye Coco	Raccoon	*Procyon lotor*	LPC	19A:623	A	L Humerus
4257	Caye Coco	Common opossum	*Didelphis marsupialis*	LPC	38:1202:6	A	R Humerus

Table D.1 Continued.

Lab #	Site	Common Name	Scientific Name	Time Period	Context	Age	Skeletal Element
4258	Caye Coco	Nine-banded armadillo	*Dasypus novemcinctus*	LPC	19B:622	A	R Humerus
4259	Caye Coco	Nine-banded armadillo	*Dasypus novemcinctus*	LPC	27:781	A	L Humerus
4260	Caye Coco	Nine-banded armadillo	*Dasypus novemcinctus*	LPC	38:1224:7	S	L Humerus
4261	Caye Coco	Nine-banded armadillo	*Dasypus novemcinctus*	LPC	18:590	A	L Femur
4262	Caye Coco	Lowland paca	*Cuniculus paca*	LPC	38:1202:6	A	R Humerus
4263	Caye Coco	Agouti or paca	Hystricognathi	LPC	18A:677	A	L Humerus
4264	Caye Coco	Agouti	*Dasyprocta* sp.	LPC	13J:842	A	L Tibia
4267	Caye Coco	Dog	*Canis lupis familiaris*	LPC	37:1246:9	A	L Radius
4268	Caye Coco	Dog	*Canis lupis familiaris*	LPC	38:1224:7	A	L Radius
4269	Caye Coco	White-tailed deer	*Odocoileus virginianus*	LPC	18E:1223:6	A	L Distal 1st Phalanx
4270	Caye Coco	White-tailed deer	*Odocoileus virginianus*	LPC	38:1127:2	A	Phalanx
4271	Caye Coco	White-tailed deer	*Odocoileus virginianus*	LPC	13J:842:4	A	R 1st Phalanx
4272	Caye Coco	White-tailed deer	*Odocoileus virginianus*	LPC	28F:1015:6	A	L 1st Phalanx
4273	Caye Coco	White-tailed deer	*Odocoileus virginianus*	LPC	29E:1003:2	A	L 1st Phalanx
4274	Caye Coco	White-tailed deer	*Odocoileus virginianus*	LPC	18:590:1	A	L 1st Phalanx
4275	Caye Coco	White-tailed deer	*Odocoileus virginianus*	LPC	19B:622:3	A	R Distal 1St Phalanx
4276	Caye Coco	Brocket deer	*Mazama* sp.	LPC	23:748:D	A	L Humerus
4277	Caye Coco	Brocket deer	*Mazama* sp.	LPC	28F:1015:6	A	L Astragalus
4278	Caye Coco	Brocket deer	*Mazama* sp.	LPC	18C:925:2	A	R Humerus
4279	Caye Coco	Brocket deer	*Mazama* sp.	LPC	18A:689:1	A	R Tibia
4280	Caye Coco	Turkey	*Meleagris* sp.	LPC	31:835	A	R Tibiotarsus
4281	Caye Coco	Turkey	*Meleagris* sp.	LPC	37:1246:9	A	L Tibiotarsus
4282	Caye Coco	Turkey	*Meleagris* sp.	LPC	37:1246:9	A	L Tibiotarsus
4285	Caye Coco	Turkey	*Meleagris* sp.	LPC	18:626	A	R Tibiotarsus
4287	Caye Coco	Mesoamerican slider	*Trachemys venusta*	LPC	38:1202:6	A	Scapula
4288	Caye Coco	Mesoamerican slider	*Trachemys venusta*	LPC	37:1201:8	A	Scapula
4290	Chanlacan	Peccary	Tayassuidae	LPC/ECol	211B:2392:	A	Rib
4292	Chanlacan	White-tailed deer	*Odocoileus virginianus*	LPC/ECol	211A:2401	A	Radius
4293	Chanlacan	Dog	*Canis lupus familiaris*	LPC/ECol	219H/I:2653	A	Tibia
4294	Chanlacan	Agouti	*Dasyprocta* sp.	LPC/ECol	219H/I:2653	A	R Calcaneus
4295	Chanlacan	Nine-banded armadillo	*Dasypus novemcinctus*	LPC/ECol	211A:2400:1	A	L Femur
4296	Chanlacan	Brocket deer	*Mazama* sp.	LPC/ECol	219H/I:2653	A	L Radius
4297	Chanlacan	Turkey	*Meleagris* sp.	LPC/ECol	211A:2402:3	A	L Tibiotarsus
4298	Chanlacan	Crocodile	Crocodylidae	LPC/ECol	211A:2402:3	A	Long bone
4299	Chanlacan	Dog	*Canis lupus familiaris*	Col	13B:2162:3	A	Tibia

Table D.1 Continued.

Lab #	Site	Common Name	Scientific Name	Time Period	Context	Age	Skeletal Element
4300	Chanlacan	Rabbit	Leporidae	Col	1A:6	A	Humerus
4301	Chanlacan	Nine-banded armadillo	*Dasypus novemcinctus*	Col	1A:6	A	Ulna
4302	Chanlacan	Nine-banded armadillo	*Dasypus novemcinctus*	Col	13B:2157:2	A	L Femur
4303	Chanlacan	White-tailed deer	*Odocoileus virginianus*	TC	1A:2000	A	Phalanx
4304	Chanlacan	Brocket deer	*Mazama* sp.	Col	13C:2175:3	A	Metacarpal
4305	Chanlacan	Peccary	Tayassuidae	Col	13E:2244:4	A	Distal Metapodial
4306	Chanlacan	Peccary	Tayassuidae	Col	13C:2175:3	A	Scapula
4307	Chanlacan	Turkey	*Meleagris* sp.	Col	1E:2022	A	Tarsometatarsus
4308	Chanlacan	Pond turtle	Emydidae	Col	1E:2022	A	Os coxa
4311	Chanlacan	White-tailed deer	*Odocoileus virginianus*	PC	915A:2802:3	A	1st Phalanx
4309	Laguna de On Shore	Nine-banded armadillo	*Dasypus novemcinctus*	C	3:1B	A	Maxilla
4312	Caye Muerto	White-tailed deer	*Odocoileus virginianus*	EPC	5:3008	A	Fragment
4313	Caye Muerto	Turkey	*Meleagris* sp.	EPC	5:2014	A	L Tibiotarsus
4314	Caye Muerto	Crocodile	Crocodylidae	EPC	5:3011	A	Cranium
4315	Nakum	cf. White-tailed deer	cf. *Odocoileus virginianus*	TC	VI-20-3-3	A	Ulna
4316	Nakum	cf. White-tailed deer	cf. *Odocoileus virginianus*	TC	VI-21-6-2	A	L Humerus
4317	Nakum	cf. White-tailed deer	cf. *Odocoileus virginianus*	L-TC	III-5-2-2	A	Metacarpal
4318	Nakum	Mesoamerican Slider	*Trachemys venusta*	TC	VI-22-5	A	Femur
4319	Nakum	cf. White-tailed deer	cf. *Odocoileus virginianus*	TC	VI-4-2-4	A	Metacarpal
4320	Nakum	White-tailed deer	*Odocoileus virginianus*	TC	VI-28-8-4	A	Tibia
4322	Nakum	Deer	Cervidae	TC	VI-22-5	S	Mandible
4323	Nakum	White-tailed deer	*Odocoileus virginianus*	LC	VI-12-1	A	Tibia
4324	Nakum	Deer	Cervidae	LC	VI-22-1-7	A	Mandible
4325	Nakum	White-tailed deer	*Odocoileus virginianus*	LC	VI-2-6	A	Metacarpal
4326	Nakum	cf. White-tailed deer	*cf. Odocoileus virginianus*	EC	VI-31A-12-3	A	Long Bone
4327	Nakum	Brocket deer	*Mazama* sp.	ProtoC	VI-6A-2	A	Cranium
4328	Nakum	cf. White-tailed deer	cf. *Odocoileus virginianus*	TC	VI-28-2-7	A	L Innominate
4329	Nakum	White-tailed deer	*Odocoileus virginianus*	TC	XIII-3-1-9	A	Scapula
4330	Nakum	Turkey	*Meleagris* sp.	TC	VI-22-5-1	A	Tibiotarsus
4331	Nakum	Deer	Cervidae	TC	VI-20-2-5	A	Metacarpal
4332	Nakum	Deer	Cervidae	LC	VI-20-2-4	A	Metacarpal
4519	Vista Alegre	Loggerhead sea turtle	*Caretta*	PC	3A-3-2	A	Neural
4520	Vista Alegre	Red brocket deer	*Mazama americana*	PC	3A-3-2	A	Astragalus
4521	Vista Alegre	Ocellated turkey	*Meleagris ocellata*	PC	3A-3-2	A	Femur

Table D.1 Continued.

Lab #	Site	Common Name	Scientific Name	Time Period	Context	Age	Skeletal Element
4522	Vista Alegre	Atlantic snapper	Lutjanidae	PC	3A-6-1	A	Caudal Vertebra
4523	Vista Alegre	Mesoamerican slider	*Trachemys venusta*	PC	3A-6-1	A	Long Bone
4524	Vista Alegre	Limpkin	*Aramus guarauna*	PC	3A-6-1	A	Tibiotarsus
4525	Vista Alegre	Ocellated turkey	*Meleagris ocellata*	PC	3A-6-1	A	Tarsometatarsus
4526	Vista Alegre	Limpkin	*Aramus guarauna*	PC	3A-6-1	A	Tibiotarsus
4527	Vista Alegre	Brocket deer	*Mazama* sp.	PC	3A-6-1	A	Mandible
4528	Vista Alegre	Loggerhead sea turtle	*Caretta caretta*	PC	3A-6-1	A	Rib
4529	Vista Alegre	Limpkin	*Aramus guarauna*	PC	3A-7-1	A	Tibiotarsus
4530	Vista Alegre	White-tailed deer	*Odocoileus virginianus*	PC	3A-7-2	A	Femur
4531	Vista Alegre	Crevalle jack	*Caranx hippos*	PC	3A-7-3	A	Vertebra
4532	Vista Alegre	Limpkin	*Aramus guarauna*	PC	3A-7-4	A	Tibiotarsus
4533	Vista Alegre	White-tailed deer	*Odocoileus virginianus*	PC	1:Pozo2:3	A	Phalanx
4534	Vista Alegre	Loggerhead sea turtle	*Caretta caretta*	PC	1:Pozo2:3	A	Fibula
4535	Vista Alegre	White-tailed deer	*Odocoileus virginianus*	PC	3B-2-1	A	Phalanx
4536	Vista Alegre	Ocellated turkey	*Meleagris ocellata*	PC	3B-2-1	A	Femur
4537	Vista Alegre	Ocellated turkey	*Meleagris ocellata*	PC	3B-2-1	A	Femur
4539	Oxtankah	Lowland paca	*Cuniculus paca*	EC	Chultun 1 Level II	A	Mandible
4540	Oxtankah	Central American agouti	*Dasyprocta punctata*	EC	Chultun 1 Level II	A	Mandible
4541	Oxtankah	Central American agouti	*Dasyprocta punctata*	EC	Chultun 1 Level II	A	Cranium
4542	Oxtankah	Virginia opossum	*Didelphis virginiana*	EC	Chultun 1 Level III	A	Mandible
4544	Oxtankah	Grey four-eyed opossum	*Philander opossum*	EC	Chultun 1 Level II	A	Mandible
4545	Oxtankah	Brocket deer	*Mazama* sp.	EC	Chultun 1 Level II	A	Astragalus
4546	Oxtankah	White-tailed deer	*Odocoileus virginianus*	EC	Chultun 1 Level II	A	Phalanx
4549	Oxtankah	Marine mammal	Mammalia	EC	Chultun 1 Level II	A	Rib
4551	Ichpaatun	Nine-banded armadillo	*Dasypus novemcinctus*	PC	C5	A	Femur
4553	Ichpaatun	Loggerhead sea turtle	*Caretta caretta*	PC	B:4	A	Scapula
4554	San Miguelito	Brocket deer	*Mazama* sp.	PC	2M	A	Mandible
4555	San Miguelito	White-tailed deer	*Odocoileus virginianus*	PC	45	A	Humerus
4563	Caracol	White-tailed deer	*Odocoileus virginianus*	TC	CD 3A/16B4 s. wall	A	L Mandible
4564	Caracol	White-tailed deer	*Odocoileus virginianus*	TC	CD 3A/27 B4 s. wall	A	R Mandible
4584	Xunantunich	Turkey	*Meleagris* sp.	LC	Op. 196 J123 Deposit 2 Tunnel in Castillo	A	L Ulna
4585	Xunantunich	White-tailed deer	*Odocoileus virginianus*	LC	Op. 141 K/5 A&A17 Intersection	A	L Humerus
4586	Xunantunich	Collared Peccary	*Pecari tajacu*	LC	Op. 1E 7/6 x41b	A	R Radius
4587	Tayasal	Central American river turtle	*Dermatemys mawii*	PC/Col	T33 2042-1391 *1)#510	A	Plastron
4588	Tayasal	Brocket deer	*Mazama* sp.	PC/Col	T52 1875-1747 n. 2 #3271	A	Metacarpal

Table D.1 Continued.

Lab #	Site	Common Name	Scientific Name	Time Period	Context	Age	Skeletal Element
4589	Tayasal	White-tailed deer	*Odocoileus virginianus*	PC/Col	T52 1879-1750 (2)	A	Metacarpal
4590	Tayasal	Collared peccary	*Pecari tajacu*	PC/Col	T52 n2 #360	A	Humerus
4591	Tayasal	Mexican musk turtle	*Staurotypus triporcatus*	PC/Col	T53 n. 2 1874-1734	A	Costal

Time periods: PreC=Preclassic; LPreC=Late Preclassic; ProtoC=ProtoClassic; C=Classic; EC=Early Classic; E-LC=Early to Late Classic Transition; LC=Late Classic; L-TC=Late to Terminal Classic; TC=Terminal Classic; PC=Postclassic; EPC=Early Postclassic; E-LPC=Early to Late Postclassic Transition; LPC=Late Postclassic; PC-Col=Postclassic to Colonial Transition; Col=Colonial; ECol=Early Colonial
Age: A=Adult; S=Subadult
Skeletal Element: L=Left; R=Right

Table D.2 Isotopic and compositional data for individual Maya faunal samples.

Lab #	Site	Common Name	$\delta^{13}C$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VCDT, ‰)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S	Collagen Yield (%)
2575	Pacbitun	Deer	-19.17	4.16	16.9	35.08	12.54	0.20	3.3	480	147	1.80
3443	Pacbitun	White-tailed deer	-20.05	5.30	17.7	36.07	12.81	0.17	3.3	572	174	4.85
3444	Pacbitun	White-tailed deer	-21.54	3.84	17.1	33.70	12.05	0.18	3.3	508	156	2.59
3445	Pacbitun	White-tailed deer	-21.80	3.35	6.5	42.87	15.65	0.24	3.2	484	152	3.17
3446	Pacbitun	White-tailed deer	-19.03	6.77	13.8	41.77	15.13	0.21	3.2	538	167	2.55
3447	Pacbitun	White-tailed deer	-19.76	6.66		23.68	7.09		***3.9***			0.83
3448	Pacbitun	Brocket deer	-22.13	4.82	15.0	42.35	15.52	0.22	3.2	509	160	5.40
3449	Pacbitun	Brocket deer	-21.44	3.78	15.5	39.23	14.20	0.17	3.2	615	191	3.90
3450	Pacbitun	Lowland paca	-24.42	8.55	13.6	41.87	15.13	0.22	3.2	517	160	4.87
3451	Pacbitun	Lowland paca	-12.15	5.14	15.5	42.47	15.37	0.21	3.2	551	171	5.43
3452	Pacbitun	Lowland paca	-21.30	2.32	18.8	28.65	10.11	0.15	3.3	496	150	3.90
3453	Pacbitun	Agouti	-21.34	2.08	17.2	37.75	13.39	0.19	3.3	524	159	3.54
3454	Pacbitun	Peccary	-21.99	4.01	15.2	44.04	16.05	0.21	3.2	557	174	9.04
3455	Pacbitun	White-lipped peccary	-19.54	4.59	14.8	35.14	12.91	0.17	3.2	542	171	3.79
3456	Pacbitun	Turkey	-20.68	4.64	15.8	43.79	16.19	0.20	3.2	587	186	8.40
3457	Pacbitun	Feline	-17.92	8.70	14.5	43.71	15.90	0.24	3.2	486	151	3.14
3458	Pacbitun	Turtle	-22.22	8.06	13.3	36.82	13.46	0.17	3.2	571	179	4.53
3459	Pacbitun	Turtle	-24.28	10.52	13.8	43.67	16.12	0.15	3.2	756	239	1.92
3460	Pacbitun	Turtle	-24.09	10.37	15.6	42.94	15.87	***0.14***	3.2	830	263	1.14
3461	Pacbitun	Turtle	-22.67	6.82	13.5	42.60	15.41	0.22	3.2	519	161	2.64
3462	Moho Cay	Caribbean manatee	-4.44	3.82	2.4	31.54	11.09	0.21	3.3	397	120	1.14
4150	Laguna de On Island	Weasel	-20.01	5.67	12.4	46.96	17.10	0.23	3.2	549	171	6.77
4152	Laguna de On Island	Opossum	-20.19	6.49	13.5	41.13	15.03	0.26	3.2	423	133	1.62
4153	Laguna de On Island	Wild turkey	-22.29	11.44	13.6	44.77	16.30	0.24	3.2	495	155	2.60
4154	Laguna de On Island	Wild turkey	-10.35	7.69	14.9	44.63	16.04	0.24	3.2	506	156	2.55
4155	Laguna de On Island	Sea turtle	-21.06	10.62	14.2	46.31	16.71	0.20	3.2	614	190	3.39
4157	Laguna de On Island	Dog	-7.56	6.62	12.6	46.09	16.98	0.22	3.2	566	179	3.76
4159	Laguna de On Island	White-tailed deer	-22.67	5.24	14.0	47.33	17.36	0.22	3.2	584	184	6.09
4160	Laguna de On Island	White-tailed deer	-23.35	4.82	15.5	44.71	16.01	0.21	3.3	573	176	2.74

Table D.2 Continued.

Lab #	Site	Common Name	$\delta^{13}C$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VCDT, ‰)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S	Collagen Yield (%)
4161	Laguna de On Island	White-tailed deer	-22.19	4.41	8.6	47.64	17.68	0.21	3.1	609	194	4.52
4162	Laguna de On Island	White-tailed deer	-18.78	4.76	12.5	44.88	16.31	0.19	3.2	637	198	1.85
4163	Laguna de On Island	White-tailed deer	-22.52	4.83	13.5	46.37	16.15	0.21	3.3	586	175	4.42
4165	Laguna de On Island	White-tailed deer	-21.13	5.07	11.7	44.46	15.31	0.21	3.4	578	171	3.74
4166	Laguna de On Island	White-tailed deer	-21.17	5.62	13.3	46.16	16.35	0.21	3.3	600	182	4.65
4168	Laguna de On Island	Peccary	-22.51	3.16	11.8	43.44	14.94	0.21	3.4	565	167	4.50
4169	Laguna de On Island	White-lipped peccary	-21.06	3.74	14.6	46.06	16.10	0.20	3.3	623	187	5.20
4170	Laguna de On Island	White-lipped peccary	-22.05	4.14	11.1	43.75	15.24	0.18	3.3	659	197	1.64
4173	Laguna de On Island	Nine-banded armadillo	-18.84	6.61	14.6	45.46	15.46	0.24	3.4	503	147	2.19
4175	Laguna de On Island	Opossum	-20.36	8.25	13.8	45.22	15.98	0.24	3.3	494	150	1.82
4176	Laguna de On Island	Nine-banded armadillo	-15.93	7.63	13.5	44.47	15.40	0.23	3.4	516	153	2.46
4178	Laguna de On Island	Nine-banded armadillo	-20.11	7.39	11.7	47.50	16.80	0.24	3.3	534	162	4.74
4179	Laguna de On Island	Nine-banded armadillo	-20.11	7.91	12.8	39.14	13.59	0.20	3.4	530	158	0.73
4180	Laguna de On Island	Nine-banded armadillo	-20.55	8.53	13.9	44.95	15.29	0.24	3.4	504	147	6.31
4181	Laguna de On Island	Red brocket deer	-23.20	6.80	13.9	45.82	15.97	0.20	3.3	627	187	4.44
4182	Laguna de On Island	Red brocket deer	-22.96	5.73	13.3	37.97	13.19	0.19	3.4	547	163	2.31
4186	Laguna de On Island	Brocket deer	-22.02	4.02	14.5	47.31	16.45	0.21	3.4	612	183	4.72
4189	Laguna de On Island	Crocodile	-15.80	10.33	8.6	43.23	15.06	0.25	3.3	470	140	1.64
4190	Laguna de On Island	Crocodile	-19.89	9.31	13.3	46.49	16.49	0.24	3.3	514	156	4.88
4192	Laguna de On Island	Crocodile	-23.12	7.29	4.6	47.31	16.74	0.25	3.3	514	156	6.55
4193	Laguna de On Island	Crocodile	-21.81	8.66	6.8	47.00	16.58	0.24	3.3	514	155	3.71

Table D.2 Continued.

Lab #	Site	Common Name	$\delta^{13}C$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VCDT, ‰)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S	Collagen Yield (%)
4194	Laguna de On Island	Mesoamerican slider	-24.80	7.12	10.2	43.97	14.75	0.20	3.5	581	167	0.94
4195	Laguna de On Island	Mesoamerican slider	-22.16	12.38	13.6	43.60	15.07	0.17	3.4	680	201	1.88
4196	Laguna de On Island	Mesoamerican slider	-25.30	7.14	2.6	42.79	15.13	0.18	3.3	637	193	1.87
4197	Laguna de On Island	Freshwater turtle	-23.02	4.03	3.9	43.53	14.84	0.19	3.4	627	183	1.47
4200	Laguna de On Island	Freshwater turtle	-15.50	10.36	9.5	41.87	13.88	0.22	3.5	503	143	1.60
4201	Laguna de On Island	Freshwater turtle	-9.86	10.31	11.2	44.95	15.91	0.20	3.3	593	180	1.97
4202	Laguna de On Island	Freshwater turtle	-18.99	14.26		41.42	13.60		***3.6***			0.60
4203	Laguna de On Island	Freshwater turtle	-18.01	10.94	10.1	40.96	14.11	0.20	3.4	535	158	1.19
4205	Laguna de On Island	Freshwater turtle	-25.91	9.36	13.4	42.59	13.58	0.24	***3.7***	481	132	2.31
4207	Laguna de On Island	Sea catfish	-16.12	8.90	6.8*	43.92	15.49	***0.30***	3.3	***390***	***118***	4.09
4208	Laguna de On Island	Sea catfish	-11.15	10.99	6.2*	44.87	16.00	***0.31***	3.3	***387***	***118***	2.59
4210	Laguna de On Island	Sea catfish	-14.82	8.64	7.5*	42.06	14.72	***0.30***	3.3	***369***	***111***	2.40
4211	Laguna de On Island	Sea catfish	-12.52	10.90		44.13	15.67		3.3			3.38
4212	Laguna de On Island	Sea catfish	-13.09	12.19		43.74	15.56		3.3			2.12
4213	Laguna de On Island	Sea catfish	-13.77	10.04	8.2*	46.27	16.34	***0.36***	3.3	***346***	***105***	2.12
4214	Laguna de On Island	Freshwater catfish	-14.81	9.91	8.9*	43.20	15.26	***0.31***	3.3	***378***	***114***	2.80
4215	Laguna de On Island	Freshwater catfish	-16.59	9.55		42.15	14.78		3.3			3.58
4250	Caye Coco	Mojarra	-19.12	12.90		36.81	11.73		***3.7***			0.82
4252	Caye Coco	Crocodile	-23.16	10.16		42.72	14.98		3.3			7.83
4253	Caye Coco	Peccary	-22.98	5.12		38.80	13.69		3.3			1.20
4254	Caye Coco	Peccary	-22.13	3.34	12.4	43.25	15.51	0.22	3.3	524	161	2.89
4255	Caye Coco	Peccary	-21.07	4.24	12.5	45.64	16.28	0.21	3.3	584	178	7.83
4256	Caye Coco	Raccoon	-20.28	2.95		30.50	10.30		3.5			0.34
4257	Caye Coco	Common opossum	-14.16	9.27	13.3	46.20	16.51	0.25	3.3	501	153	3.84

Table D.2 Continued.

Lab #	Site	Common Name	$\delta^{13}C$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VCDT, ‰)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S	Collagen Yield (%)
4258	Caye Coco	Nine-banded armadillo	-19.78	8.06	12.2	44.53	15.63	0.26	3.3	464	140	2.31
4259	Caye Coco	Nine-banded armadillo	-17.03	8.54	13.2	44.78	16.08	0.23	3.2	526	162	4.26
4260	Caye Coco	Nine-banded armadillo	-22.91	6.81	12.4	41.55	14.05	0.24	3.5	468	136	4.02
4261	Caye Coco	Nine-banded armadillo	-20.71	8.84	9.5	44.20	15.55	0.29	3.3	413	124	0.42
4262	Caye Coco	Lowland paca	-17.50	6.58	13.0	47.75	17.10	0.23	3.3	551	169	7.59
4263	Caye Coco	Agouti or paca	-19.87	5.21	12.8	45.17	15.67	0.32	3.4	379	113	2.91
4264	Caye Coco	Agouti	-19.91	4.70	14.8	42.09	15.16	0.21	3.2	540	167	2.19
4267	Caye Coco	Dog	-12.70	9.59	8.5	45.45	16.42	0.23	3.2	532	165	8.40
4268	Caye Coco	Dog	-9.23	7.61	10.7	47.75	17.05	0.22	3.3	571	175	4.90
4269	Caye Coco	White-tailed deer	-22.32	4.53		40.90	14.39		3.3			1.46
4270	Caye Coco	White-tailed deer	-22.62	3.45	12.1	43.30	15.26	0.21	3.3	562	170	3.48
4271	Caye Coco	White-tailed deer	-22.52	3.51	14.0	44.21	15.73	0.26	3.3	452	138	2.81
4272	Caye Coco	White-tailed deer	-22.08	4.66	12.2	44.94	15.61	0.23	3.4	518	154	5.45
4273	Caye Coco	White-tailed deer	-21.35	6.35	12.3	45.82	16.46	0.21	3.2	586	180	7.91
4274	Caye Coco	White-tailed deer	-22.60	5.44	17.1*	41.79	13.92	***0.50***	3.5	***222***	***63***	1.53
4275	Caye Coco	White-tailed deer	-21.02	7.41	14.1	47.41	16.70	0.23	3.3	554	167	5.85
4276	Caye Coco	Brocket deer	-22.67	4.69	13.9	32.81	11.78	0.22	3.3	403	124	7.20
4277	Caye Coco	Brocket deer	-23.50	5.00	14.0	42.92	14.62	0.22	3.4	527	154	2.39
4278	Caye Coco	Brocket deer	-22.40	5.33	15.9	43.46	15.26	0.29	3.3	396	119	2.38
4279	Caye Coco	Brocket deer	-22.81	6.52	13.0	38.29	13.48	0.21	3.3	482	145	4.21
4280	Caye Coco	Turkey	-8.28	7.04	14.7	41.52	14.57	0.27	3.3	407	122	1.88
4281	Caye Coco	Turkey	-8.38	7.33	13.7	44.91	16.07	0.24	3.3	495	152	6.08
4282	Caye Coco	Turkey	-11.93	7.59	10.7	45.80	16.40	0.24	3.3	509	156	4.26
4285	Caye Coco	Turkey	-11.66	9.03		37.68	12.85		3.4			0.64
4287	Caye Coco	Mesoamerican slider	-23.23	7.15	8.5	44.41	16.16	0.17	3.2	689	215	4.42
4288	Caye Coco	Mesoamerican slider	-27.21	8.90	12.3	44.93	16.39	0.18	3.2	651	204	2.92
4290	Chanlacan	Peccary	-21.61	3.96	13.0	43.84	14.75	0.23	3.5	511	147	2.66
4292	Chanlacan	White-tailed deer	-22.33	3.76	13.0	42.34	14.85	0.22	3.3	525	158	3.54
4293	Chanlacan	Dog	-21.68	8.16	3.0	45.29	16.34	0.26	3.2	472	146	2.89
4294	Chanlacan	Agouti	-20.33	2.65	13.7	44.08	16.09	0.19	3.2	611	191	3.84
4295	Chanlacan	Nine-banded armadillo	-20.35	8.22	13.8	43.45	15.20	0.24	3.3	485	145	1.72
4296	Chanlacan	Brocket deer	-23.25	4.60	13.2	43.36	15.65	0.21	3.2	561	174	4.10
4297	Chanlacan	Turkey	-6.75	6.42	14.0	44.29	15.51	0.24	3.3	490	147	3.01
4298	Chanlacan	Crocodile	-4.33	6.69		35.72	12.42		3.4			0.71

Table D.2 Continued.

Lab #	Site	Common Name	$\delta^{13}C$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VCDT, ‰)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S	Collagen Yield (%)
4299	Chanlacan	Dog	-20.64	9.60	12.2	43.91	15.91	0.24	3.2	480	149	3.59
4300	Chanlacan	Rabbit	-19.71	5.10	14.2	43.97	15.80	0.19	3.2	607	187	1.69
4301	Chanlacan	Nine-banded armadillo	-20.12	6.60	13.2	44.00	15.70	0.23	3.3	515	157	2.92
4302	Chanlacan	Nine-banded armadillo	-20.34	6.41	14.0	45.47	16.24	0.25	3.3	485	148	4.63
4303	Chanlacan	White-tailed deer	-22.47	6.06	13.8	44.52	16.05	0.20	3.2	606	187	5.23
4304	Chanlacan	Brocket deer	-21.82	6.03	14.3	44.60	15.88	0.21	3.3	556	170	3.30
4305	Chanlacan	Peccary	-7.26	8.06	8.1	44.69	16.24	0.21	3.2	569	177	9.43
4306	Chanlacan	Peccary	-19.50	6.97	13.3	45.40	16.10	0.21	3.3	571	174	5.46
4307	Chanlacan	Turkey	-8.61	7.00	13.2	42.76	15.30	0.24	3.3	479	147	4.13
4308	Chanlacan	Pond turtle	-22.03	8.78	2.3	43.69	15.67	0.18	3.3	658	202	5.79
4311	Chanlacan	White-tailed deer	-22.48	3.39	12.4	43.60	15.68	0.20	3.2	596	184	4.23
4309	Laguna de On Shore	Nine-banded armadillo	-21.05	4.04	15.8	43.68	15.81	0.19	3.2	607	188	6.39
4312	Caye Muerto	White-tailed deer	-20.20	3.94	13.3	43.16	15.50	0.20	3.2	575	177	3.29
4313	Caye Muerto	Turkey	-21.26	3.05		43.26	15.05		3.4			3.71
4314	Caye Muerto	Crocodile	-10.97	6.47		40.43	14.32		3.3			0.90
4315	Nakum	cf. White-tailed deer	-21.31	3.82	14.4	46.28	16.54	0.21	3.3	582	178	3.39
4316	Nakum	cf. White-tailed deer	-18.35	7.02		42.34	14.78		3.3			0.30
4317	Nakum	cf. White-tailed deer	-21.67	4.41	14.5	45.92	16.25	0.18	3.3	665	202	4.29
4318	Nakum	Mesoamerican Slider	-22.59	7.46	14.6	46.08	16.40	0.17	3.3	706	215	4.73
4319	Nakum	cf. White-tailed deer	-22.42	6.00	14.4	47.17	16.76	0.22	3.3	562	171	5.22
4320	Nakum	White-tailed deer	-20.25	6.42	12.7	44.44	15.57	0.21	3.3	568	171	2.81
4322	Nakum	Deer	-21.57	1.53	12.8	45.18	15.75	0.21	3.3	566	169	4.95
4323	Nakum	White-tailed deer	-21.06	3.82	13.1	43.56	15.20	0.20	3.3	596	178	3.36
4324	Nakum	Deer	-20.59	6.35	12.5	45.29	16.28	0.20	3.2	610	188	4.50
4325	Nakum	White-tailed deer	-20.38	6.59	5.0	46.50	16.61	0.33	3.3	376	115	5.45
4326	Nakum	cf. White-tailed deer	-19.82	6.78	13.5	47.11	16.59	0.21	3.3	587	177	3.36
4327	Nakum	Brocket deer	-19.63	6.34	12.9	44.06	15.68	0.20	3.3	602	184	2.88
4328	Nakum	cf. White-tailed deer	-20.74	4.68	13.9	45.46	16.11	0.21	3.3	577	175	3.74
4329	Nakum	White-tailed deer	-21.86	4.21	13.0	45.61	16.33	0.23	3.3	529	162	3.69
4330	Nakum	Turkey	-21.27	6.05	14.0	45.11	15.60	0.23	3.4	525	156	3.36
4331	Nakum	Deer	-21.35	4.58	13.8	46.42	16.43	0.19	3.3	638	194	3.47
4332	Nakum	Deer	-21.44	5.93	13.5	45.29	16.35	0.19	3.2	637	197	3.34
4519	Vista Alegre	Loggerhead sea turtle	-12.42	10.30	11.1	41.70	15.20	0.17	3.2	658	206	1.46
4520	Vista Alegre	Red brocket deer	-22.63	6.67	14.9	42.40	14.98	0.17	3.3	657	199	1.59

Table D.2 Continued.

Lab #	Site	Common Name	$\delta^{13}C$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VCDT, ‰)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S	Collagen Yield (%)
4521	Vista Alegre	Ocellated turkey	-9.98	7.42	15.7	43.00	15.50	0.23	3.2	499	154	2.31
4522	Vista Alegre	Atlantic snapper	-2.63	8.61	-1.3	44.10	15.90	0.49	3.2	***238***	74	4.55
4523	Vista Alegre	Mesoamerican slider	-9.35	7.64	3.4	42.50	15.30	0.19	3.2	606	187	1.64
4524	Vista Alegre	Limpkin	-11.01	7.45	13.5	43.00	15.40	0.23	3.3	496	152	3.44
4525	Vista Alegre	Ocellated turkey	-11.37	7.89	15.0	42.70	15.40	0.24	3.2	480	149	3.12
4526	Vista Alegre	Limpkin	-10.98	8.00	14.2	43.60	15.60	0.23	3.3	503	154	2.77
4527	Vista Alegre	Brocket deer	-10.73	6.21	14.2	43.50	15.40	0.20	3.3	577	175	5.16
4528	Vista Alegre	Loggerhead sea turtle	-13.59	11.12	13.6	42.50	15.40	0.17	3.2	671	208	2.89
4529	Vista Alegre	Limpkin	-9.98	7.19	16.0	43.40	15.50	0.24	3.3	474	145	2.26
4530	Vista Alegre	White-tailed deer	-20.88	5.06	15.1	43.60	15.70	0.21	3.2	562	173	2.69
4531	Vista Alegre	Crevalle jack	-8.25	10.35	12.0*	41.60	15.20	0.43	3.2	***259***	***81***	1.97
4532	Vista Alegre	Limpkin	-8.47	7.17	16.0	44.10	15.50	0.27	3.3	442	133	2.44
4533	Vista Alegre	White-tailed deer	-20.76	6.32	12.6	42.00	14.89	0.24	3.3	470	143	2.34
4534	Vista Alegre	Loggerhead sea turtle	-20.01	6.95	13.5	43.70	15.70	0.20	3.2	598	184	1.96
4535	Vista Alegre	White-tailed deer	-7.35	8.45		38.80	13.82		3.3			0.50
4536	Vista Alegre	Ocellated turkey	-11.81	7.66	13.1	43.40	15.50	0.23	3.3	503	154	2.08
4537	Vista Alegre	Ocellated turkey	-9.95	6.37	16.5	43.10	15.40	0.22	3.3	530	162	1.91
4539	Oxtankah	Lowland paca	-20.02	5.82	16.6	43.50	15.60	0.22	3.3	*535*	164	4.41
4540	Oxtankah	Central American agouti	-19.88	5.57	18.0	41.90	14.94	0.19	3.3	*588*	180	2.47
4541	Oxtankah	Central American agouti	-19.56	6.68	15.8	41.80	14.85	0.21	3.3	*523*	159	3.33
4542	Oxtankah	Virginia opossum	-19.57	6.41		40.80	14.16		3.4			0.83
4544	Oxtankah	Grey four-eyed opossum	-19.36	7.86	14.8	41.90	15.00	0.25	3.3	445	137	3.04
4545	Oxtankah	Brocket deer	-17.10	7.43	16.0	43.20	15.30	0.25	3.3	454	138	3.19
4546	Oxtankah	White-tailed deer	-17.16	7.45	16.0	44.20	15.90	0.22	3.2	543	167	5.03
4549	Oxtankah	Marine mammal	-17.25	7.54	16.1	44.60	15.90	0.23	3.3	524	160	6.69
4551	Ichpaatun	Nine-banded armadillo	-19.86	6.20	16.5	44.70	16.00	0.21	3.3	557	171	8.06
4553	Ichpaatun	Loggerhead sea turtle	-7.60	4.79	-2.8*	44.40	15.70	***0.37***	3.3	322	***98***	4.75
4554	San Miguelito	Brocket deer	-20.31	7.26	13.7	44.40	15.90	0.23	3.3	524	161	7.23
4555	San Miguelito	White-tailed deer	-19.68	7.36	12.3	44.90	15.90	0.26	3.3	456	138	9.33
4563	Caracol	White-tailed deer	-20.34	3.91		43.30	15.60		3.2			2.64
4564	Caracol	White-tailed deer	-20.48	3.90		44.35	15.85		3.3			4.35
4584	Xunantunich	Turkey	-7.40	7.96		44.70	16.10		3.2			1.58
4585	Xunantunich	White-tailed deer	-21.42	4.70	16.7	44.25	15.75	0.18	3.3	657	200	6.59
4586	Xunantunich	Collared Peccary	-20.87	6.32	14.9	44.60	16.00	0.17	3.3	698	215	3.51

Table D.2 Continued.

Lab #	Site	Common Name	$\delta^{13}C$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VCDT, ‰)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S	Collagen Yield (%)
4587	Tayasal	Central American river turtle	-19.65	9.04		42.60	15.10		3.3			1.26
4588	Tayasal	Brocket deer	-23.51	4.42		41.00	14.60		3.3			4.06
4589	Tayasal	White-tailed deer	-21.49	5.14		45.60	16.00		3.3			2.43
4590	Tayasal	Collared peccary	-22.60	3.99		44.30	15.70		3.3			2.85
4591	Tayasal	Mexican musk turtle	-20.99	6.08		42.10	14.70		3.3			1.23

Note: Bolded and italicized values fall beyond acceptable diagenetic parameters.
*Isotopic values with more than one outlying diagenetic indicator that were removed from analysis.

APPENDIX E

OSTEOLOGICAL, CONTEXTUAL, AND ISOTOPIC DATA FOR THE MAYA HUMAN SAMPLES

Table E.1: Osteological and contextual data for the Maya human samples.

Lab #	Site	Burial/ID Number	Chronology	Context	Age	Sex	Skeletal Element
2514	Caledonia	A1-1 P1	E-LC	Str. A-1 Burial 1	A	I	L 1st proximal phalanx
2515	Caledonia	A1-1 P2	E-LC	Str. A-1 Burial 1	A	I	L 1st proximal phalanx
2516	Caledonia	A1-1 P3	E-LC	Str. A-1 Burial 1	A	I	L 1st proximal phalanx
2517*	Caledonia	A1-1 P4	E-LC	Str. A-1 Burial 1	A	I	L 1st proximal phalanx
2518	Caledonia	A1-1 P5	E-LC	Str. A-1 Burial 1	A	I	L 1st proximal phalanx
2519	Caledonia	A1-1 J	E-LC	Str. A-1 Burial 1	3-5	I	R femur
2520	Caledonia	C2-3A	LC	Str. C-2 Burial 3	MA	M?	L tibia
2521	Caledonia	C2-3B	LC	Str. C-2 Burial 3	YA	I	L tibia
2522	Caledonia	C2-3C	LC	Str. C-2 Burial 3	YA	M	R tibia
2523	Caledonia	C2-3D	LC	Str. C-2 Burial 3	A	F?	R tibia
2524*	Caledonia	C2-4A	LC	Str. C-2 Burial 3	A	M?	Mandible
2525*	Caledonia	C2-4B	LC	Str. C-2 Burial 4	A	I	Mandible
2526*	Caledonia	C2-4C	LC	Str. C-2 Burial 4	A	F?	Mandible
2527*	Caledonia	C2-4D	LC	Str. C-2 Burial 4	A	I	Mandible
2528*	Caledonia	C2-4E	LC	Str. C-2 Burial 4	A	I	Mandible
2529	Caledonia	C2-4 F1	LC	Str. C-2 Burial 4	A	I	R fibula
2530	Caledonia	C2-4 F2	LC	Str. C-2 Burial 4	A	I	R fibula
2531	Caledonia	C2-4 F3	LC	Str. C-2 Burial 4	A	I	R fibula
2532	Caledonia	C2-4 F4	LC	Str. C-2 Burial 4	A	I	R fibula
2533	Caledonia	C2-4 F5	LC	Str. C-2 Burial 4	A	I	R fibula
2534	Caledonia	C2-4 F6	LC	Str. C-2 Burial 4	A	I	R fibula
2535	Caledonia	C2-4 F7	LC	Str. C-2 Burial 4	A	I	R fibula
2536	Caledonia	C1-5A	LPreC	Str. C-1 Burial 5	OA	F	L tibia
4406	Caledonia	A1-1	E-LC	Str. A-1 Burial 1 Vessel 3	A	I	L 3rd metatarsal
2549*	Pacbitun	BU 1-6	EC	Str. 1 Burial 6	50-60	M	Long bone
2550	Pacbitun	BU 1-1	LC	Str. 1 Burial 1 (Lot 37)	20-40	F	Long bone
2551	Pacbitun	BU 2-4	LC	Str. 2 Burial 4 (Lot 82)	40+	M	Long bone
2552*	Pacbitun	BU 4-2	LC	Str. 4 Burial 2	A	M	Long bone
2553*	Pacbitun	BU 1-7	TC	Str. 1 Burial 7	A	M	Long bone
2554*	Pacbitun	BU 2-1	TC	Str. 2 Burial 1	A	F	Fibula
2555	Pacbitun	BU 2-2	TC	Str. 2 Burial 2 (Lot 30)	35-40	M	Long bone
2556*	Pacbitun	BU 2-5	TC	Str. 2 Burial 5 (Lot 62)	6-7	I	Long bone
2557	Pacbitun	BU 4-3	PA	Str. 4 Burial 3 (Fill)	A	F	Fragment
2558	Pacbitun	Lot 302 Individual 1[a]	TC	SE Quad Str. 6 Burial 1 (Lot 302)	A	F?	Fragment
2559	Pacbitun	Lot 302 Individual 2[a]	TC	SE Quad Str. 6 Burial 1 (Lot 302)	<6	I	Fragment

Table E.1 Continued.

Lab #	Site	Burial/ID Number	Chronology	Context	Age	Sex	Skeletal Element
2560	Pacbitun	Lot 304 Individual 1	TC	SE Quad Str. 6 Burial 3 (Lot 304)	OA	I	Fragment
2561	Pacbitun	Lot 304 Individual 2	TC	SE Quad Str. 6 Burial 3 (Lot 304)	A	I	Fragment
2562*	Pacbitun	Lot 472	TC	NE Quad Str. 52 Burial 2 (Lot 472)	OA	F?	Crania
2563	Pacbitun	Lot 486	TC	SW Quad Str. 36 Burial 1 (Lot 486)	A	M	Long bone
2564*	Pacbitun	BU 1-2	LC	Str. 1 Burial 2 (Lot 61)	A	M	Femur
2565*	Pacbitun	BU 1-4	LC	Str. 1 Burial 4 (Lot 87)	A	F	Femur
2566*	Pacbitun	BU 1-5	LPreC	Str. 1 Burial 5 (Lot 125)	A	M	Mandible
2567*	Pacbitun	BU 1-9	LC	Str. 1 Burial 9 (Lot 327)	40-50	M	Long bone
2568*	Pacbitun	BU 4-1	LC	Str. 4 Burial 1 (Lot 179)	A	F	Long bone
2569*	Pacbitun	BU 5-1	LC	Str. 5 Burial 1 (Lot 35)	A	M	Ulna/radius
2570*[,b]	Pacbitun	DU	LC	Str. 1 below Phase 4 Floor Lot 333	DU	DU	Long bone
2571	Pacbitun	Lot 331	TC	SE Quad Str. 6 Burial 4 (Lot 331)	OA	M	Long bone
2572*	Pacbitun	Lot 471	TC	NE Quad Str. 52 Burial 1 (Lot 471)	50+	F?	Long bone
2573	Pacbitun	BU 5-2	TC	Str. 5 Burial 2 (Lot 127)	A	I	Long bone
2574*	Pacbitun	Lot 479	TC	NW Quad Str. 33 Burial 1 (Lot 479)	A	I	Long bone
4497	Nakum	Burial 4	TC	Burial 4 (I-14-1-8)	4-6	I	R ulna
4498	Nakum	Burial 7	M-LPreC	Burial 7 (I-13)	A	I	Long bone
4499*	Nakum	Burial 5	EC	Burial 5 (I-2A)	A	F	R tibia
4500	Nakum	Ulna/radius III-1-2	TC	III-1-2	A	I	Ulna/radius
4506*	Nakum	Humerus VI-6A-1	LC	VI-6A-1	A	I	R humerus
4507	Nakum	Burial 2	ProtoC	Burial 2 (VI-3A-10)	45-50	F	Femur
4509*	Nakum	Burial 1	LC	Burial 1 (VI-3-8 con 4)	35-45	I	Long bone
4511	Nakum	Patella VI-8-14a	EC	VI-8-14a	A	I	L patella
4516*	Nakum	Burial 8	E-LC	Burial 8 (I-6B-1-7)	A	I	Femur
4566*	San Lorenzo	Op. 71 C/2	LC I	Op. 71 C/2 Deposit 1	A	I	Tibia
4567	San Lorenzo	Op. 243 LL/3	LC II or TC	Op. 243 LL/3	35-45	F	R ulna
4568*	San Lorenzo	Op. 386 B/5	LC IIB	Op. 386 B/5	DU	DU	L humerus
4569*	San Lorenzo	Op. 386 H/26	LC IIB	Op. 386 H/26	A	DU	Fragment
4570*	San Lorenzo	Op. 386 H/58	LC IIB	Op. 386 H/58	3-5	DU	East leg
4571*	San Lorenzo	Op. 386 J/15	LC IIB	Op. 386 J/15	DU	DU	Fragment
4572*	San Lorenzo	Op. 388 E/5 Individual 2	LC IIB	Op. 388 E/5	A	DU	Femur/tibia
4573*	Xunantunich	Op. 211 K/07	LC II	Op. 211 K/07	A	F	Femur/tibia
4574	Xunantunich	Op. 302 G	LC II or TC	Op. 302 G	20-23	M	R humerus

Table E.1: Continued.

Lab #	Site	Burial/ID Number	Chronology	Context	Age	Sex	Skeletal Element
4575	Xunantunich	Op. 21 C Individual 1	LPreC	Op. 21 C/1 Individual 1	50	M	L tibia
4576*	Xunantunich	Op. 21 C Individual 2	LPreC	Op. 21 C/1 Individual 2	25-29	M	L tibia
4577	Xunantunich	Op. 74 R	TC	Op. 74 R/1	A	I	L femur
4578*	Xunantunich	8g-10	LPreC	8g-10	A	M	West tibia
4579	Xunantunich	B5 B-5/1	LC II	B5 B-5/1	A	F?	Long bone
4580	Xunantunich	E3 4b-24 B2	LC II	E3 4b-24 B2	A	M?	Fragment
4581*	Xunantunich	E3 4b-24 B3	LC II	E3 4b-24 B3	A	M?	Long bone
4582*	Xunantunich	XN Individual 1	EC	Str. B5 looter's trench	A	DU	L femur
4583	Xunantunich	XN Individual 2	TC or EPC	Str. B5 looter's trench	A	DU	L femur
4592*	San Bernabé	Burial 1	Col	Str. T31 Burial 1	A	F	L clavicle
4593	San Bernabé	Burial 5A	Col	Str. T31 Burial 5A	A	F	R clavicle
4594	San Bernabé	Burial 18	Col	Str. T31 Burial 18	YA	M	R clavicle
4595	San Bernabé	Burial 19	Col	Str. T31 Burial 19	A	F	L clavicle
4596	San Bernabé	Burial 22A	Col	Str. T31 Burial 22A	YA	M	L clavicle
4597	San Bernabé	Burial 23	Col	Str. T31 Burial 23	OA	M	L clavicle
4598	San Bernabé	Burial 26	Col	Str. T31 Burial 26	A	M?	R clavicle
4599	San Bernabé	Burial 27	Col	Str. T31 Burial 27	YA	M	R clavicle
4600*	San Bernabé	Burial 30	Col	Str. T31 Burial 30	6-12	I	L humerus
4601	San Bernabé	Burial 33	Col	Str. T31 Burial 33	2-5	I	R tibia
4753*	Calakmul	F5328	DU	Ent 1 (1631) Caja 3	DU	DU	Fragment
4754*	Calakmul	F5330	DU	Ent XV-2 Tumba II Caja 5	DU	DU	Radius
4755*	Calakmul	F5331	DU	Ent XV-3 Tumba III Caja 6	DU	DU	Femur
4756*	Calakmul	F5332	DU	Estr. IV-8 Ent. 2 Caja 8	DU	DU	L femur
4757	Calakmul	F5335	DU	Ent. 2 Caja 10 Lat. Oeste Mas 1	DU	DU	Fragment
4758*	Calakmul	F5336	DU	Ent 3(A) Estr II Caja 11	DU	DU	Femur
4759*	Calakmul	F5340	DU	Estr. II Ent. 2C Caja 14	DU	DU	Femur
4760*	Calakmul	F5341	DU	Ent. II-2 Caja 16	DU	DU	Fragment
4761*	Calakmul	F5342	DU	Ent 4 Estr II Temp 97-98 Caja 17	DU	DU	Femur
4762*	Calakmul	F5343	DU	Estr II Ent 5A? Caja 18	DU	DU	Radius
4763*	Chac II	Ent. 28-1A (F2528)	EC	Grupo Platforma Pozo 28 Entierro 1	A	F?	R humerus
4764*	Chac II	Ent. 31-1 (F2529)	E-LC	Grupo Platforma Pozo 31 Entierro 1	A	F	Fragment
4765*	Chac II	Ent. 31-7 (F2530)	E-LC	Grupo Platforma Pozo 31 Entierro 7	DU	DU	Long bone
4766*	Chac II	Ent. 31-6 (F2532)	E-LC	Grupo Platforma Pozo 31 Entierro 6	A	M	Femur
4767*	Chac II	Ent. 32-2 (F2534)	E-LC	Grupo Platforma Pozo 32 Entierro 2	A	M?	Femur
4768*	Chac II	Ent. 72-5 (F2537)	E-LC	Grupo Sacta Pozo 72 Entierro 5	~3.5	I	Cranium

Table E.1: Continued.

Lab #	Site	Burial/ID Number	Chronology	Context	Age	Sex	Skeletal Element
4769*	Chac II	Ent. 94-8 (F2538)	E-LC	Grupo Sacta Pozo 94 Entierro 8	1-2.5	I	L humerus
4770*	Chac II	F2536	E-LC	Grupo Platforma Entierro 13	DU	DU	Long bone
4771*	Chac II	F2542	DU	Grecas Subop 135 Entierro 1	DU	DU	Radius

Age: A = Adult; YA = Young Adult; MD = Middle Adult; OA = Older Adult; DU = Data Unavailable; Age ranges are in years.
Sex: F=Female; F?=Probable Female; I=Indeterminate; M?=Probable Male; M=Male; UA=Under Analysis; DU=Data Unavailable.
*Excluded from Chapter 4 discussion due to lack of collagen, $\delta^{13}C$, $\delta^{15}N$, or $\delta^{34}S$ values.
[a]Based on lack of burial information as well as $\delta^{13}C$ and $\delta^{15}N$ values, this sample is likely an animal that was misidentified as human.
Note: Time periods can be found in the notes for Table D.1.

Table E.2: Isotopic and compositional data for individual Maya human samples.

Lab #	Site	Burial/ID Number	$\delta^{13}C$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VCDT, ‰)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S	Collagen Yield (%)
2514	Caledonia	A1-1 P1	-9.17	8.10	9.77[a]	43.26	15.31	0.22	3.3	515	156	10.25
2515	Caledonia	A1-1 P2	-10.56	7.41	11.54[a]	41.55	14.71	0.22	3.3	506	154	13.14
2516	Caledonia	A1-1 P3	-8.60	8.04	10.91[a]	42.40	15.40	0.20	3.2	557	173	4.52
2517*	Caledonia	A1-1 P4	-	-	11.82[a]	-	-	0.20	-	-	-	7.80
2518	Caledonia	A1-1 P5	-8.55	8.86	10.96[a]	47.90	17.20	0.22	3.2	575	177	8.42
2519	Caledonia	A1-1 J	-11.77	11.62	9.43[a]	38.25	13.76	0.20	3.2	502	155	8.57
2520	Caledonia	C2-3A	-12.94	8.36	8.25[b]	31.34	11.09	0.15	3.3	546	166	2.82
2521	Caledonia	C2-3B	-7.82	7.67	12.72[a]	43.65	15.49	0.30	3.3	389	118	8.41
2522	Caledonia	C2-3C	-11.13	8.79	9.89[a]	39.30	14.13	0.20	3.2	524	161	2.42
2523	Caledonia	C2-3D	-8.46	10.52	13.37[a]	43.90	15.85	0.19	3.2	613	190	3.45
2524*	Caledonia	C2-4A	-	-	-	-	-	-	-	-	-	0.00
2525*	Caledonia	C2-4B	-11.09	9.92	12.82[a]	42.40	15.40	0.20	3.2	554	173	2.58
2526*	Caledonia	C2-4C	-7.99	7.86	11.62[a]	40.80	14.38	0.21	3.3	523	158	4.06
2527*	Caledonia	C2-4D	-7.70	8.75	12.14[a]	41.00	14.77	0.19	3.2	569	176	1.74
2528*	Caledonia	C2-4E	-12.02	9.06	12.79[a]	41.22	14.48	0.20	3.3	552	166	3.94
2529	Caledonia	C2-4 F1	-8.33	9.60	11.20[a]	40.80	14.86	0.20	3.2	541	169	0.70
2530	Caledonia	C2-4 F2	-13.22	8.60	7.98[a]	41.90	15.10	0.20	3.2	550	170	2.29
2531	Caledonia	C2-4 F3	-10.88	8.62	10.29[a]	42.90	15.50	0.21	3.2	555	172	3.33
2532	Caledonia	C2-4 F4	-8.64	9.22	12.25[a]	43.25	15.75	0.19	3.2	598	187	3.48
2533	Caledonia	C2-4 F5	-10.24	9.27	12.10[b]	42.90	15.60	0.20	3.2	569	177	3.81
2534	Caledonia	C2-4 F6	-8.39	10.62	15.87[b]	42.90	15.60	***0.14***	3.2	841	262	2.09
2535	Caledonia	C2-4 F7	-13.17	8.52	7.87[a]	40.70	14.80	0.19	3.2	587	183	2.29
2536	Caledonia	C1-5A	-12.26	8.56	11.82[a]	40.20	14.41	0.23	3.3	476	146	0.80
4406	Caledonia	A1-1	-7.86	9.20	11.58[a]	44.90	16.15	0.20	3.2	609	188	6.57
2549*	Pacbitun	BU 1-6	-	-	-	-	-	-	-	-	-	***0.00***
2550	Pacbitun	BU 1-1	-9.48	9.45	12.02[a]	35.92	11.92	0.20	3.5	484	138	1.86
2551	Pacbitun	BU 2-4	-7.54	8.89	12.33[a]	41.68	14.61	0.21	3.3	529	159	2.19
2552*	Pacbitun	BU 4-2	-	-	-	-	-	-	-	-	-	***0.00***
2553*	Pacbitun	BU 1-7	-	-	-	-	-	-	-	-	-	***0.01***
2554*	Pacbitun	BU 2-1	-9.71	9.30	-	23.77	7.37	-	***3.8***	-	-	1.86
2555	Pacbitun	BU 2-2	-8.97	9.88	11.86[a]	34.05	11.96	0.17	3.3	531	160	1.58
2556*	Pacbitun	BU 2-5	-	-	13.14[a]	-	-	0.20	-	-	-	***0.46***

Table E.2 Continued.

Lab #	Site	Burial/ID Number	$\delta^{13}C$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VCDT, ‰)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S	Collagen Yield (%)
2557	Pacbitun	BU 4-3	-13.26	7.52	12.52[a]	35.12	12.17	0.20	3.4	471	140	5.93
2558	Pacbitun	Lot 302 Individual 1[d]	-10.19	8.83	11.45[a]	42.03	15.10	0.19	3.2	581	179	3.64
2559	Pacbitun	Lot 302 Individual 2[d]	-10.09	7.79	12.20[a]	42.15	14.86	0.22	3.3	513	155	3.10
2560	Pacbitun	Lot 304 Individual 1	-8.99	8.95	12.62[a]	40.79	14.56	0.21	3.3	508	155	3.02
2561	Pacbitun	Lot 304 Individual 2	-11.10	8.12	13.29[a]	34.96	12.24	0.18	3.3	507	152	3.48
2562*	Pacbitun	Lot 472	-	-	-	-	-	-	-	-	-	***0.39***
2563	Pacbitun	Lot 486	-9.16	9.85	13.13[a]	34.72	12.23	0.19	3.3	490	148	5.12
2564*	Pacbitun	BU 1-2	-	-	-	-	-	-	-	-	-	***0.00***
2565*	Pacbitun	BU 1-4	-	-	-	-	-	-	-	-	-	***0.01***
2566*	Pacbitun	BU 1-5	-	-	-	-	-	-	-	-	-	***0.00***
2567*	Pacbitun	BU 1-9	-	-	-	-	-	-	-	-	-	***0.00***
2568*	Pacbitun	BU 4-1	-	-	-	-	-	-	-	-	-	***0.34***
2569*	Pacbitun	BU 5-1	-	-	-	-	-	-	-	-	-	***0.17***
2570*[,c]	Pacbitun	N/A	-21.46	3.47	-	43.07	15.64	-	3.2	-	-	1.54
2571	Pacbitun	Lot 331	-9.78	8.64	13.56[a]	34.12	10.77	0.24	***3.7***	387	105	1.28
2572*	Pacbitun	Lot 471	-11.42	9.52	-	34.21	12.35	-	3.2	-	-	0.79
2573	Pacbitun	BU 5-2	-13.30	9.11	14.73[a]	33.03	11.97	0.18	3.2	498	155	1.64
2574*	Pacbitun	Lot 479	-	-	-	-	-	-	-	-	-	***0.00***
4497	Nakum	Burial 4	-14.16	10.04	13.40[a]	41.52	14.58	0.23	3.3	492	148	1.48
4498	Nakum	Burial 7	-13.91	10.00	13.11[a]	42.25	14.73	0.21	3.3	547	163	1.16
4499*	Nakum	Burial 5	-	-	-	-	-	-	-	-	-	0.00
4500	Nakum	Ulna/Radius III-1-2	-10.54	11.06	13.25[a]	42.08	15.04	0.18	3.3	620	190	1.91
4506*	Nakum	Humerus VI-6A-1	-	-	-	-	-	-	-	-	-	0.16
4507	Nakum	Burial 2	-9.88	6.09	12.93[a]	41.60	13.18	0.21	***3.7***	533	145	0.97
4509*	Nakum	Burial 1	-	-	-	-	-	-	-	-	-	0.00
4511	Nakum	Patella VI-8-14a	-9.63	11.13	12.89[a]	43.36	14.93	0.25	3.4	463	137	1.97
4516*	Nakum	Burial 8	-	-	-	-	-	-	-	-	-	0.00
4566*	San Lorenzo	Op. 71 C/2	-	-	-	-	-	-	-	-	-	0.42
4567	San Lorenzo	Op. 243 LL/3	-12.21	9.47	13.44[c]	44.40	16.10	0.15	3.2	794	247	3.64
4568*	San Lorenzo	Op. 386 B/5	-9.85	7.88	-	44.30	15.90	-	3.3	-	-	6.81
4569*	San Lorenzo	Op. 386 H/26	-13.52	9.65	-	44.90	16.10	-	3.3	-	-	6.27
4570*	San Lorenzo	Op. 386 H/58	-9.24	9.94	-	42.80	15.40	-	3.2	-	-	5.86

Table E.2 Continued.

Lab #	Site	Burial/ID Number	$\delta^{13}C$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VCDT, ‰)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S	Collagen Yield (%)
4571*	San Lorenzo	Op. 386 J/15	-	-	-	-	-	-	-	-	-	0.80
4572*	San Lorenzo	Op. 388 E/5 Individual 2	-	-	-	-	-	-	-	-	-	0.16
4573*	Xunantunich	Op. 211 K/07	-9.21	9.27	-	41.40	14.77		3.3	-	-	2.47
4574	Xunantunich	Op. 302 G	-9.19	10.12	16.18[c]	45.85	16.55	0.15	3.2	796	246	6.05
4575	Xunantunich	Op. 21 C Individual 1	-12.71	8.70	14.33[c]	43.00	15.10	0.19	3.3	614	185	1.99
4576*	Xunantunich	Op. 21 C Individual 2	-	-	-	-	-	-	-	-	-	0.61
4577	Xunantunich	Op. 74 R	-12.10	10.52	13.28[c]	45.60	15.80	0.18	3.4	689	205	2.68
4578*	Xunantunich	8g-10	-	-	-	-	-	-	-	-	-	0.00
4579	Xunantunich	B5 B-5/1	-9.05	10.42	13.68[c]	44.90	15.80	0.17	3.3	692	209	1.73
4580	Xunantunich	E3 4b-24 B2	-12.62	8.30	13.67[c]	42.90	15.20	0.21	3.3	541	164	4.41
4581*	Xunantunich	E3 4b-24 B3	-11.58	10.27	-	41.40	14.41	-	3.4	-	-	0.89
4582*	Xunantunich	XN Individual 1	-11.63	8.69	-	42.90	15.40	-	3.3	-	-	3.44
4583	Xunantunich	XN Individual 2	-10.79	8.69	14.12[c]	44.90	16.20	0.18	3.2	671	207	2.22
4592*	San Bernabé	Burial 1	-9.48	8.78	-	41.85	14.86	-	3.3	-	-	5.52
4593	San Bernabé	Burial 5A	-7.92	9.75	14.59[c]	46.70	16.50	0.17	3.3	733	222	2.95
4594	San Bernabé	Burial 18	-8.78	10.27	14.64[c]	39.20	14.00	0.30	3.3	351	108	4.90
4595	San Bernabé	Burial 19	-8.24	9.95	15.00[c]	45.80	16.60	0.18	3.2	683	212	5.02
4596	San Bernabé	Burial 22A	-7.62	9.71	15.27[c]	42.20	15.20	0.16	3.2	710	219	3.43
4597	San Bernabé	Burial 23	-7.54	10.19	15.25[c]	44.50	16.20	***0.14***	3.2	836	261	2.61
4598	San Bernabé	Burial 26	-8.27	9.88	15.34[c]	44.10	16.00	***0.14***	3.2	814	253	2.62
4599	San Bernabé	Burial 27	-7.48	9.92	15.84[c]	44.60	16.10	***0.13***	3.2	890	275	3.59
4600*	San Bernabé	Burial 30	-8.18	8.86	-	41.20	14.49	-	3.3	-	-	3.27
4601	San Bernabé	Burial 33	-8.00	10.25	16.04[c]	44.20	15.80	***0.13***	3.3	***928***	284	10.21
4753*	Calakmul	F5328	-	-	-	-	-	-	-	-	-	0.00
4754*	Calakmul	F5330	-	-	-	-	-	-	-	-	-	0.00
4755*	Calakmul	F5331	-	-	-	-	-	-	-	-	-	0.00
4756*	Calakmul	F5332	-	-	-	-	-	-	-	-	-	0.00
4757	Calakmul	F5335	-9.63	9.89	17.36[c]	44.30	15.75	***0.13***	3.3	899	274	8.02
4758*	Calakmul	F5336	-	-	-	-	-	-	-	-	-	0.00
4759*	Calakmul	F5340	-11.07	13.90	-	44.00	15.80	-	3.2	-	-	0.77

Table E.2 Continued.

Lab #	Site	Burial/ID Number	$\delta^{13}C$ (VPDB, ‰)	$\delta^{15}N$ (AIR, ‰)	$\delta^{34}S$ (VCDT, ‰)	%C	%N	%S	Atomic C:N	Atomic C:S	Atomic N:S	Collagen Yield (%)
4760*	Calakmul	F5341	-11.63	12.02	-	43.30	15.70	-	3.2	-	-	0.90
4761*	Calakmul	F5342	-	-	-	-	-	-	-	-	-	0.00
4762*	Calakmul	F5343	-	-	-	-	-	-	-	-	-	0.00
4763*	Chac II	Ent. 28-1A (F2528)	-12.30	9.49	-	40.90	13.90	-	3.4	-	-	2.07
4764*	Chac II	Ent. 31-1 (F2529)	-	-	-	-	-	-	-	-	-	0.00
4765*	Chac II	Ent. 31-7 (F2530)	-	-	-	-	-	-	-	-	-	0.00
4766*	Chac II	Ent. 31-6 (F2532)	-	-	-	-	-	-	-	-	-	0.00
4767*	Chac II	Ent. 32-2 (F2534)	-	-	-	-	-	-	-	-	-	0.00
4768*	Chac II	Ent. 72-5 (F2537)	-	-	-	-	-	-	-	-	-	0.00
4769*	Chac II	Ent. 94-8 (F2538)	-	-	-	-	-	-	-	-	-	0.00
4770*	Chac II	F2536	-	-	-	-	-	-	-	-	-	0.00
4771*	Chac II	F2542	-	-	-	-	-	-	-	-	-	0.00

Note: Bolded and italicized values fall beyond acceptable diagenetic parameters. Samples with more than one outlying diagenetic value were removed from the analysis, as indicated by a strikethrough.

*Excluded from Chapter 4 discussion due to lack of collagen, $\delta^{13}C$, $\delta^{15}N$, or $\delta^{34}S$ data.

[a]Sample analysed at the University of Tennessee

[b]Sample analysed at the Memorial University of Newfoundland

[c]Sample analyzed at the University of Ottawa

[d]Listed at Lot 301 in published studies (Coyston et al. 1999; White et al. 1993) but identified as Lot 302 in reports (Campbell-Trithart 1990).

[e]Based on lack of burial information as well as $\delta^{13}C$ and $\delta^{15}N$ values, this sample is likely an animal that was misidentified as human.