Mobility and Collapse: Stable Isotope Analysis of Oxygen-18 Isotopes from Ancient Mexico

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Melanie L. St. Pierre
University of Central Florida

Mobility and Collapse: Stable Isotope Analysis of Oxygen-18 Isotopes from Ancient Mexico

by

Melanie St. Pierre

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Abstract

When a society experiences a collapse, political authority becomes decentralized, large settlements often become abandoned, economic specialization decreases; and monumental building projects, artistic, and literary achievements slow drastically. The Rio Verde Valley, a coastal floodplain located in the region of Oaxaca in Southwest Mexico, experienced such a collapse at the end of the Terminal Formative period (150 BC to 250 AD). A period of decentralization followed, with regional centers becoming the main seats of authority throughout the region. My aim is to understand how this collapse affected residential population mobility in the lower Rio Verde Valley between the pre-collapse Terminal Formative and post-collapse Early Classic periods. I seek to answer the question: could this political collapse have caused intra-regional migration amongst the people of Ancient Oaxaca? To answer this, I analyzed the stable ^{18}O and ^{13}O isotopes in a set of 21 samples of human long bone excavated from the Terminal Formative archaeological site of Yugüe and the Early Classic site of Charco Redondo. Oxygen isotope analysis is based on the principle that bone apatite and tooth enamel hold traces of oxygen isotopes found in the water that people drink, and that varying values of those isotopes reflect that the water was obtained from different sources. Based on literature surrounding the process of political collapse in ancient Mesoamerica and beyond, I expected to find evidence that intra-regional population mobility increased after the Terminal Formative period collapse. Instead, I found evidence of little to no mobility in both the Terminal Formative period site and the Early Classic period site, showing that the political collapse likely did not affect intraregional mobility. These findings provide valuable insight into how human migration patterns correspond

with political changes, both in the archaeological record of past civilizations and in modern societies.

Dedication

For Mom and Dad, who have always pushed me to follow my dreams,

and to Zach, who has supported me in this project even through all the sleepless nights

Acknowledgements

A year ago, I walked into Dr. Sarah Barber's office with only the inkling of an idea and a passion to delve deeper into my field. I never anticipated that she would drop a box of two-thousand year old bones in my lap and ask me to conduct an isotopic study on them as an undergraduate research project. I cannot thank Dr. Barber enough for presenting me with this amazing opportunity and for being such a positive influence over the course of this research. I could not have come this far without her advice, encouragement, and expertise on Mesoamerican archaeology. I also want to extend a huge amount of gratitude to Dr. Marla Toyne for spending so much time with me in the lab and going above and beyond to teach me about isotopic theory and methods. Her enthusiasm for science and anthropology has inspired me to become the best scientist I can be. I would also like to thank Michelle Butler for allowing me to cite her dissertation work on Charco Redondo—vital information that has contributed immensely to my understanding of the Rio Verde Valley. Finally, I have so much love and gratitude for my family and friends, who have stuck by my side and provided endless support even through the stress and tears. Zach, you have been my biggest cheerleader, and you have celebrated with me every step along the way. I would not have discovered this passion if not for my dad, who first shared with me his love of science, and my mom, who has always pushed me to follow my dreams.

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Chapter 1: Introduction

What is Collapse?

The process of political collapse within a society is complex and variable, with causes ranging from internal unrest to environmental factors or even conflict with rival groups. Tainter (1988:4) describes collapse as a sociopolitical process, and defines it as “a rapid, significant loss of an established level of sociopolitical complexity.” With societal collapse comes a lower degree of social stratification; less economic specialization; less centralized control; less monumental building projects, literary, and artistic achievements; a slowed flow of information and trade; less organization of individuals and groups; and smaller territories within polities. Urban and political centers are also often partially or completely abandoned (Schwartz and Nichols 2010), which suggests that population mobility is an inherent result of political collapse. As Schwartz and Nichols (2010:6) assert, “…rarely does collapse involve the complete disappearance of a group of people.” Although not commonly mentioned or discussed in speculations on the workings of political collapse, it has been documented that people often may respond to the dissolution of their known society by moving to new areas within their region. For example, following the collapse of Teotihuacan, a mass exodus occurred. The population dispersed outward from the city center and into the more lightly populated parts of the region, where new settlements were established (Diehl 1989:18).

Tainter (1988) explains that, as a society achieves higher levels of complexity, it often peaks with a ‘golden age’ of monumental architecture, artistic expression, economic prosperity, and increased exchange of goods and ideas. At a certain point, however, complexity becomes inherently unsustainable, as growing authority requires a greater amount of resources than are available. Ultimately, every society experiences a collapse. This research project focuses on human migration patterns following the political collapse of the Terminal Formative period (150 BC to AD 250) in the lower Rio Verde Valley, Oaxaca, Mexico.

Terminal Formative Collapse in the Rio Verde Valley

Archaeological evidence from the lower Rio Verde Valley suggests that the ruling elites of the major political center at Rio Viejo during the Terminal Formative period likely had a high degree of political and religious power, and may have controlled both long-distance trade and the conscription of labor for monumental building projects. Following the historically reoccurring pattern of other complex societies, authority in the polity became unstable and did not last long. The polity's administrative center of Rio Viejo collapsed fairly rapidly around AD 250. Evidence from excavation has revealed that parts of the elaborate public structure on the site's acropolis had been burned down, possibly during a violent conflict. Several other Terminal Formative period centers in the lower Rio Verde Valley had either been abandoned or had declined significantly in size by the Early Classic period (AD 250-500), though specific cause is unknown. Joyce (2010) suggests that leading up to the destruction of Rio Viejo's acropolis, tension grew between localized, traditional forms of authority and the newly emerged central authority, as well as between neighboring polities. Regardless of the cause, the result was "a period of political decentralization and a return to more local forms of authority" (Joyce 2010:196). The abandonment of urban and political centers in the Rio Verde Valley suggests that the former residents of these settlements may have migrated to new locations in the region. This period of fragmented polities and decentralized political authority spanned the Early Classic period, and it would not be until the Late Classic period that centralized political authority would re-emerge in the form of a once-again powerful Rio Viejo. (Joyce 2010)

Time Period	**Ceramic Phase**	**Dates**
Late Postclassic	Yucudzaa	A.D. 1100 - 1500
Early Postclassic	Yugüe	A.D. 800 - 1100
Late Classic	Yuta Tiyoo	A.D. 500 - 800
Early Classic	Coyuche	A.D. 250 - 500
Late Terminal Formative	Chacahua	A.D. 100 - 250
Early Terminal Formative	Miniyua	150 B.C. - A.D. 100
Late Formative	Minizundo	400 - 150 B.C.
Middle Formative	Charco	700 - 400 B.C.

Table 1: Chronology of the lower Rio Verde Valley

Research Questions

This research project asks the key question, how did the people of the lower Rio Verde Valley respond to this period of decreased complexity? The ways in which people respond to times of political unrest are as intricate and inconstant as the people themselves, but one typical response is the increase or decrease in intra-regional mobility. In this research, I aim to utilize a method known as stable isotope analysis of ^{18}O isotopes in human bone apatite in order to identify patterns of internal migration in the lower Rio Verde Valley during the transition from the Terminal Formative period to the Early Classic period—a span that navigates the urbanization of Rio Viejo and its subsequent collapse. During this time of massive social and political change, how did the pre-Columbian people of the lower Rio Verde Valley respond in terms of residential movement? Did they migrate to different areas of the region, seeking a new way of life? Or did they remain to witness the full course of the transformation? In short, my research question is as follows: Does the isotopic evidence support a model for internal mobility during the Early Classic period, and could the presence or lack of mobility be interpreted as a result of the political unrest which the region was experiencing? Previous research in the region, as well as literature surrounding the process and consequences of political collapse throughout history, suggests that population mobility was a likely outcome of collapse (Rumberger 2016; Schwartz and Nichols 2010; Diehl 1989). Therefore, I hypothesize that the isotopic evidence from my samples will support a model for population mobility following the Terminal Formative political collapse. Answering these questions will give us a clearer understanding of how human migration patterns correspond with political changes, both in the archaeological record of past civilizations and in the rapidly shifting global politics of the modern era.

Chapter 2: Background

Geography

Geographically, this research focuses on the lower Rio Verde Valley, located in the modern state of Oaxaca in what is now Mexico (Fig. 1). The Rio Verde is sourced deep in the Sierra Madre del Sur mountain range, and flows south towards the Pacific coast, where it fans out to create an alluvial floodplain which covers approximately 1,000 km^2 (Joyce 2010:41; Joyce 1991a). This coastal floodplain receives more rainfall than further inland, and temperatures are considerably higher (Joyce 1991a). The river itself acts as a drain for most of the Oaxaca highlands, carrying with it large deposits of sediment which result in nutrient-rich soil (Joyce and Mueller 1997). The warm, humid climate and fertile soil foster semi-deciduous forests, dry scrub, and mangrove trees along rivers and estuaries, and simultaneously create an ideal environment for crop cultivation. This was a major draw for the groups who settled the region (Joyce and Mueller 1992; 1997).

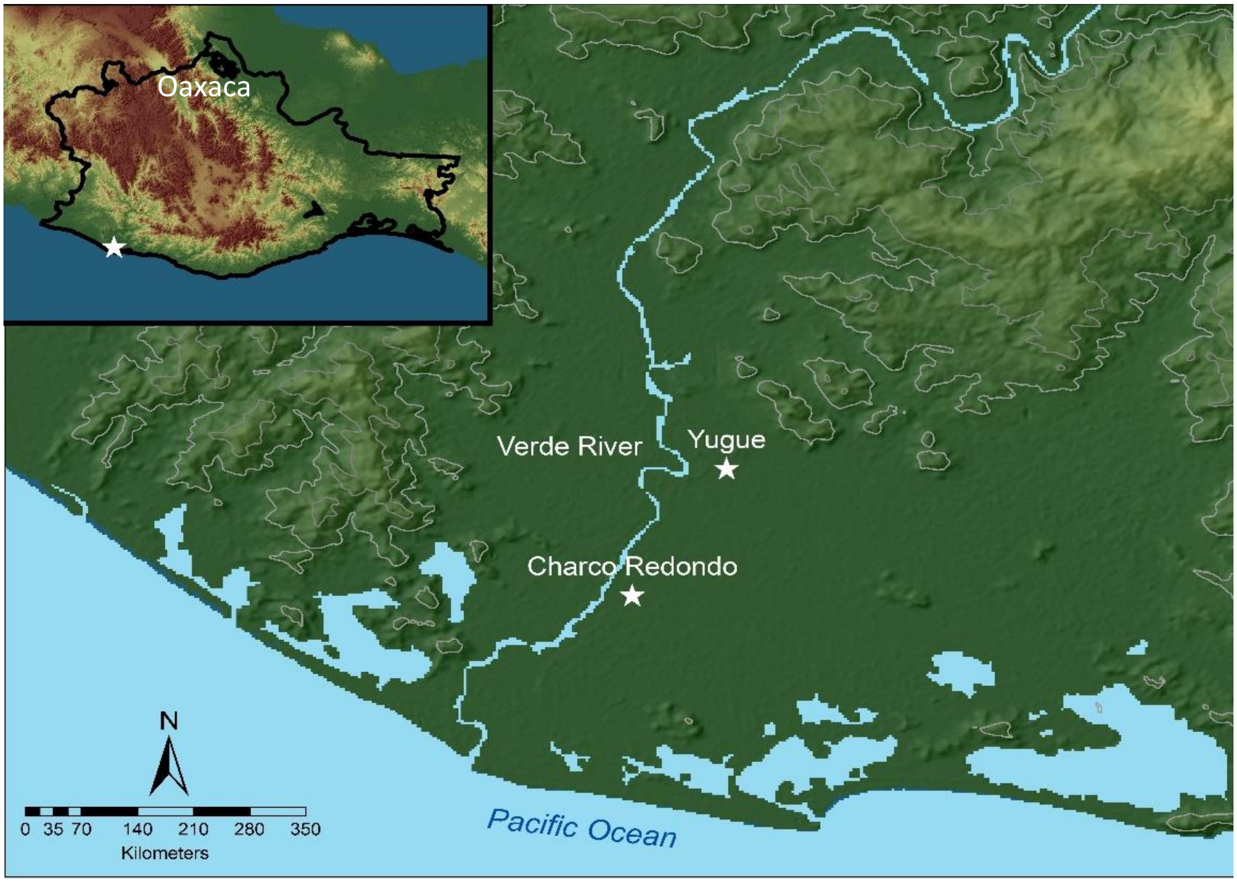

Figure 1: Location of lower Rio Verde Valley and important Terminal Formative period sites

The Chatino: Background and History

The lower Rio Verde Valley was occupied by an ethnolinguistic group known as the Chatino during the Terminal Formative and Early Classic periods (Joyce 2010). The Chatino language is a close relative of Zapotec, the language spoken in the Valley of Oaxaca, and glottochronological studies suggest that the two languages diverged between the Late and Terminal Formative periods (Josserand et al. 1984). We know from stone carvings in the Zapotec script that Chatino was being spoken at least by the Early Classic period (Joyce and Winter 1989:256). However, the inhabitants of the lower Rio Verde Valley were most likely a distinct cultural group long before they began speaking Chatino, so for the purpose of this study I will refer to them by their ethnolinguistic name.

The Terminal Formative period saw the rise of the sprawling Chatino urban and political center of Rio Viejo and several secondary urban centers like Charco Redondo and San Francisco de Arriba, as well as smaller tertiary villages like Yugüe. By the late Terminal Formative period, Charco Redondo had grown to a size of over 70 hectares and boasted a population possibly exceeding 1000 (Joyce 2010:180), while Yugüe had grown to an area of 10 hectares and boasted a large central platform as high as 10 meters above the surrounding floodplain (Joyce 2010:187). According to Joyce (2010), it is likely that the most prestigious and powerful families resided at urban centers like Rio Viejo, Charco Redondo, and San Francisco de Arriba (Joyce 2010:185). Both Yugüe and Charco Redondo, as well as seven other settlements in the lower Rio Verde valley, had large public building projects for monumental architecture before the Terminal Formative period collapse (Barber 2005:121), but by the Early Classic period, Yugüe had been abandoned. Charco Redondo, like the rest of the region, experienced a period of decentralized authority following political collapse which spanned the Early Classic period. When centralized leadership re-emerged during the Late Classic period, monumental building resumed and Rio Viejo was once again the core of a powerful Chatino polity (Joyce 2010). This study focuses on the archaeological sites of Yugüe and Charco Redondo in order to help answer questions of human mobility following Terminal Formative period political collapse.

Yugüe

Yugüe was excavated during the Proyecto Rio Verde 2003 by Sarah Barber for her PhD dissertation (Barber 2005). The site, located 2 km east of the Rio Verde and 13 km north of the Pacific Ocean, covered an area of 9.75 ha, and was abundant in natural resources and fertile soil. This attracted settlement groups as early as the late Middle Formative Charco Phase through to the late Terminal Formative Chacahua Phase (Table 1). It was reoccupied during the Late Post-classic Yucudzaa Phase and again in the historic and modern periods (Barber 2005). Most of the site's materials have been dated to the Terminal Formative period. In her dissertation, Barber describes Yugüe as a fairly 'cosmopolitan' community during the Terminal Formative. It was part of a string of settlements spread along the eastern bank of the river, and was located only 4 km away from the political center of Rio Viejo. The focal point of the site was its monumental earthen platform, which was rectangular in shape and covered an area of approximately 4.75 ha (Barber 2005; Joyce 1999b). At its summit sat three substructures. These, along with the enormous platform, would have been an architectural project that required extensively organized group labor to complete (Barber 2005). Substructure 1 indicates a long history of communal ritual activity, evidenced by numerous caches, food preparation areas, middens, and a cemetery dated to the Terminal Formative period. (Barber 2005)

Charco Redondo

The site of Charco Redondo is located ten kilometers inland from the Pacific coast and approximately 500 meters from the Río Verde. Situated only 6 km southeast of Yugüe, Charco Redondo was considerably larger and was an important urban center of the lower Rio Verde Valley, whereas Yugüe is considered to be more of a periphery settlement (Barber 2005). Like

Yugüe, the core of the site is a large platform mound, which is irregularly shaped and covers an area of approximately 35 ha. Atop this platform are at least ten monumental structures, ranging from 3 to 7 meters in height (Grove 1988). The site was occupied as early as the Early Formative period through to the Late Classic period. It covered an area of approximately 95 ha. during the Early Classic period, making it the largest settlement in the valley at the time (Joyce et al. 1998; Butler 2018). A fragmented political state spanned the entirety of the Early Classic period following the collapse at the end of the Terminal Formative, and authority did not recentralize at Rio Viejo until the Late Classic period. Prior to this political recentralization, however, how did individuals within the population respond to decreased complexity in terms of mobility? Scientifically, we can determine the presence of residential movement throughout the region using a technique known as stable isotope analysis.

Stable Isotope Analysis and Theory

Larsen (2015:3) describes bioarchaeology as "the study of human remains from archaeological contexts." Using human remains to study the behavior and societies of people and cultures from the past is the central tenet of bioarchaeology, and of this research study (Larsen 2015). Stable isotope analysis is just one of the many ways we can use biology to make inferences about ancient peoples and populations.

Isotopes are atoms of the same element, but with different numbers of neutrons. Since atomic mass is determined by the number of protons and neutrons, isotopes that have a greater number of neutrons have a higher atomic mass, and are considered 'heavy isotopes,' while isotopes with fewer neutrons are considered ‘light isotopes’ (Fry 2000; Sharp 2007). For example, the element Oxygen has three isotopes: ^{16}O, ^{17}O, and ^{18}O. ^{18}O has eighteen neutrons, and thus has a greater atomic mass than ^{16}O. Stable isotopes can survive relatively unchanged for billions of years, allowing us to access information virtually frozen in time. Within the field of bioarchaeology, this means that we are able to analyze stable isotopes including carbon, nitrogen and oxygen within human bone, enamel, and tissue remains to determine paleodiet and paleomobility (Fry 2006; Sharp 2007; Ambrose and Krigbaum 2003). While carbon and nitrogen isotopes are used primarily for reconstructing paleodiet, oxygen is generally used for tracking residential mobility (Fry 2006; Sharp 2007; Ambrose and Krigbaum 2003). This is based on the principle that, since ^{16}O isotopes are lighter than ^{18}O isotopes, H_2O molecules containing ^{16}O will evaporate faster than water molecules containing their heavier sister isotopes, resulting in a certain water source becoming more enriched with ^{18}O and depleted in ^{16}O (Daansgard 1964; Fry 2006; Sharp 2007). These changes in mixing and fractionation result in precipitation that has varying oxygen isotope values according to a number of variables including temperature, latitude, distance from the coast, and altitude, thus resulting in values that vary across geography (Epstein and Mayeda 1953; Dansgaard 1964; Knudson 2015).

When a person consumes H_2O, the oxygen isotopes in the water become incorporated into the crystalline hydroxyapatitic structure [$Ca_5(PO_4)_3(OH)$] that makes up their bones and teeth (Fry 2006; Sharp 2007; Sehrawat and Kaur 2017). Since bones are constantly being remodeled throughout the lifetime of an individual (unlike teeth, which do not remodel once the permanent set forms in adolescence), it must be noted that the isotopic data from osteological remains is representative of the last ten to twenty years of an individual’s life, therefore showing residential mobility only for that final period in life (Hedges et al. 2005, 2007; Katzenberg 2008). By extracting the oxygen isotopes from bones and teeth and then analyzing them in a mass spectrometer, we can identify the unique ratio of $^{18}O/^{16}O$ within a specific sample (Fry 2006; Sharp 2007; Sehrawat and Kaur 2017). The $\delta^{18}O$ value that results is compared to the values obtained from other samples in the set, allowing us to identify the level of variation and the possible presence of outliers, if some values vary significantly from the mean. The oxygen isotope values are measured relative to the Vienna Standard Mean Ocean Water (VSMOW) standard and are expressed in parts per mil (‰) using the following formula (Coplen 1994):

$$\delta^{18}0 = \frac{(^{18}0\ /^{16}0_{\text{sample}} - {}^{18}0/^{16}0_{\text{standard}})}{(^{18}0/^{16}0_{\text{standard}})} \quad x1000$$

^{13}C is typically analyzed as an indicator of diet rather that mobility. This is due to the process of photosynthesis within the carbon cycle. As plants photosynthesize, they absorb carbon dioxide and the carbon atoms bond with other carbon atoms to create larger molecules. Because ^{12}C is a lighter isotope than ^{13}C, it forms bonds faster. This results in plants becoming more enriched in ^{12}C than the surrounding atmosphere. This fractionation of carbon isotopes occurs differently in distinct plant species. Therefore, the ratio of ^{13}C to ^{12}C varies amongst types of plants (Lambert 1997; Deniro 1987). Wheat, rice, legumes, fruits, and nuts tend to absorb the lighter isotope of ^{12}C more than the heavier isotope, while maize, sugarcane, sorghum, and some millets absorb the heavier isotope of ^{13}C in greater quantities (Wickman 1952; Bender 1968; Rumberger 2016). When humans consume plants as a dietary component, the carbon isotopes are incorporated into the hydroxyapatite within their bones, just as with oxygen isotopes (Fry 2006;

Sharpe 2007). By analyzing these isotopes in the bone carbonate of osteological remains, we can determine what types of plants individuals consumed during the last ten years of their life. Large differences between $\delta^{13}C$ values could possibly indicate that the individual was consuming food resources in a different region, if the available food resources varied greatly from area to area. However, the region in question, the lower Rio Verde Valley, is geographically quite small and uniform in terms of food diversity (Rumberger 2016). It is therefore unlikely that the $\delta^{13}C$ values will be relevant to the context of this study, since mobility, rather than diet, is the primary focus. However, I will be reporting the carbon isotope results from this sample set so as to provide data for future avenues of research.

Diagenesis and FTIR

The substance from which we extract stable isotopes, bioapatite, is a crystallized mineral structure made of phosphates and hydroxides (Grunenwald et al. 2014). Over time, the structure of the bioapatite can become mechanically and chemically altered through poor preservation or environmental and burial conditions—a process known as diagenesis. The apatite can dissolve and recrystallize, ions can be depleted or added, and mineralization may alter the structural and chemical composition (Sasso et al. 2016). Any of these diagenetic alterations can modify stable isotope results, producing skewed or incorrect data (Grunenwald et al. 2014). In order to determine the presence of diagenetic alterations like recrystallization within the sample's apatite (and thus a greater chance of the results being incorrect), we can perform a type of spectroscopic analysis known as Fourier Transform Infrared Spectroscopy, or FTIR. This type of spectroscopy measures a sample's absorption of infrared radiation by the vibrational frequencies of its different molecular components, thus producing data which reveals the structural composition of a sample (Wright and Schwarcz 1996). Carrying out an FTIR analysis alongside a carbonate analysis allows for more confidence in the results (Shemesh 1990).

Previous Isotopic Studies within Oaxaca

Very few isotopic studies have been conducted in the region of Oaxaca. Most of the isotope work that has been conducted there has dealt with paleodiet, rather than mobility (Hepp et al. 2017; Rumberger 2016; Warinner et al. 2013; White et al. 1998). Rumberger's thesis (2016) on diet and migration in coastal Oaxaca is the primary source of information on stable isotopes and mobility in the region. Rumberger also focused on a period of collapse—that of the Classic period, rather than the Terminal Formative period, and her findings that the Early Post-classic displayed a wider range of $\delta^{18}O$ values than the Late Classic support the idea that Classic period collapse led to the regional disbursement of human populations.

Another research study of interest conducted by White et al. (1998, 2004, 2011) used ^{18}O isotopes from remains excavated at the powerful state center of Teotihuacan to track mobility. They sampled a set of remains located in one of the city's many ethnic enclaves, or barrios. This particular enclave, also known as Tlailotlacan or the Oaxaca Barrio, was believed to be inhabited by Zapotec immigrants from Oaxaca based on associated archaeological materials. The earliest evidence for Zapotec inhabitation in Teotihuacan dates to about AD 200. This would support a model for migration in Ancient Oaxaca, if not the lower Rio Verde Valley specifically, shortly before the Terminal Formative period collapse.. White and her colleagues sought to determine whether the isotopic evidence supported the archaeological evidence, and they did indeed find that the sampled remains from Tlailotlacan had $\delta^{18}O$ values that varied significantly from the values expected of native Teotihuacan residents.

Arthur Joyce's 1991 PhD dissertation included an analysis of skeletal remains excavated from the Late Formative period cemetery of Cerro de la Cruz in the lower Rio Verde valley of Oaxaca, and further research on the cemetery was conducted in a more recent study by Mayes and Joyce (2017). These included a strontium isotope analysis of 14 individuals to determine individual mobility patterns. The results indicated that all individuals except one had been raised and died in the region, suggesting that the period before Terminal Formative period collapse did not exhibit significant population mobility.

Chapter 3: Materials and Methodology

Samples and Archaeological Context

In order to determine the presence or absence of mobility as a possible result of Terminal Formative period political collapse, I analyzed the stable ^{13}C and ^{18}O isotopes found in a set of human remains from twenty-one individuals (Table 2). Additionally, I analyzed the level of preservation and presence of diagenetic alteration using FTIR spectroscopy in order to support the validity of my results. In order to provide a control, I also duplicated the samples from B17 I19 (YG.7B) and B30 I30 (CR.11B), and referred to them as YG.7BB and CR.11BB. In total, I ran 23 samples for ^{13}C, ^{18}O, and FTIR.

Burial Number	Lab ID	Bone	Sex	Age
B8 I8	YG.2B	Humerus	Female	40-50
B10 I11	YG.3B	L Humerus	N/A	6-6.8
B11 I12	YG.4B	R Humerus	N/A	6-6.8
B12 I13	YG.5B	R Femur	Female	20-25
B14 I16	YG.6B	L Femur	Male	15-17
B17 I19	YG.7B	L Femur	N/A	N/A
B29 I33	YG.10B	L Humerus	Female	30-40
B23 I29	YG.11B	L Femur	Female	30-39
B14 I15	YG.14B	L Femur	Female	35-40
B19 I19	CR.2B	L Femur	N/A	40-49
B20 I20	CR.3B	L Femur	Male	40-49
B20 I24	CR.5B	L Femur	Male	35-49

B22 I22	CR.6B	L Femur	Female	36-45
B27 I27	CR.8B	L Humerus	N/A	40-50
B28 I28	CR.9B	L Femur	Male*	35-40
B29 I29	CR.10B	L Humerus	N/A	Adult
B30 I30	CR.11B	L Femur	Male	45*
B31 I31	CR.12B	L Femur	Female*	30-40
B32 I32	CR.13B	L Femur	Male*	35-45
B32 I33	CR.14B	L Humerus	Female	50+
B34 I34	CR.15B	Femur	Male	22-30

Table 2: Table showing published burial number (Barber 2005; Butler 2018) and corresponding lab ID, demographic information of sample, and type of bone from which each sample was extracted

Nine of the samples were obtained from the femora or humeri of individuals excavated at the site of Yugüe in 2003 by Dr. Sarah Barber for her PhD dissertation as part of the Proyecto Rio Verde. The archaeological site covers an area of 9.75 ha. and represents an archaeological sequence spanning the late Middle Formative Charco Phase through the late Terminal Formative Chacahua Phase. The majority of materials date to the Terminal Formative period, right before the region began to decentralize and the acropolis at Rio Viejo fell into disuse (Joyce 2010). The burials themselves date to this period, which allows us to use samples from Yugüe to represent the period before collapse. The cemetery from which the individuals were excavated is located on Substructure 1, a community ritual structure positioned atop the site's platform. The remains of 40 individuals were excavated within an area of less than 7 m^2 (Barber and Joyce 2007:226).

Almost all were commingled and heavily disturbed by the placement of later burials, with only three individuals remaining fully articulated (Barber 2013). This is likely a result of ongoing interment over an extended period of time rather than a single mass burial (Barber and Joyce 2007). The cemetery also represents a wide demographic, with individuals of both sexes and with ages ranging from infants to older adults. Many of the burials also contained modest grave goods, like pottery and beads, suggesting those individuals belonged to the common class. However, one individual in particular, B14 I16 (YG.6B), was interred with an iron-ore pectoral disc and an elaborately carved bone flute, suggesting that he was of elite status. (Barber 2005)

The other twelve samples were obtained from the long bones of individuals excavated at Charco Redondo in 2011 by Michelle Butler for her PhD dissertation. All samples are derived from skeletal remains recovered from a cemetery dated to the Early Classic Coyuche phase, when political regionalization was fully realized in the area. The cemetery sits atop a large earthen mound that rises 3 meters above the main platform. This cemetery was a communal place of burial, where members of the community were interred over several generations. Within the 30 m^2 plot that has been excavated, 18 burials containing 27 individuals have been uncovered. In addition, the remains of four individuals were found around the perimeter of an Early Classic feasting midden associated with the cemetery, resulting in a total of 31 individuals. The individuals vary in both age and sex, which appears to be related to the varied burial positions. Thirteen of the burials also contained mortuary offerings, which generally consisted of gray and orangeware ceramic vessels, suggesting that most of the interred individuals were of common socioeconomic status. However, two of the burials, Burials 19 and 22, were quite elaborate, suggesting that the primary interments in each of them were individuals of elite status.

Burial 19 consisted of one primary individual, B19 I19 (CR.2B), and two secondary individuals, and was interred with a number of offerings including 23 vessels, one basalt handaxe, and six large granite stone lajas (slabs). Burial 22 also contained one primary adult male, B22 I22 (CR.6B), and three secondary internments, as well as 18 locally crafted ceramic vessels, one fine brownware ceramic import, ground stone, and a large stone laja, to name just a few. A strontium isotope analysis was conducted on 17 of the individuals from the cemetery in order to determine provenience. There were two outliers that most likely represent non-locals, and one possible outlier (B28 I28 (CR.9B)). The possible outlier and one of the definite outliers, B27 I27 (CR.8B), are included in my own sample set as well. (Butler 2018)

Previous isotopic studies on remains from this region conducted by Jacklyn Rumberger for her Master's thesis utilized a sample size of twenty-three individuals for both collagen and apatite analysis, so this sample size of twenty-one individuals for an undergraduate honors thesis should be more than sufficient to produce results that are representative of data for the lower Rio Verde Valley (Rumberger 2016).

Methods for Bone Apatite Extraction

Carbonate, a chemical compound derived from the mineralized apatite in bone, was prepared for ^{18}O and ^{13}C isotope analysis using methods derived from Metcalfe (2009), Garvie-Lok (2004), and Sullivan and Krueger (1983). Since bone apatite is particularly susceptible to diagenetic alterations, the samples were treated using the following process in order to remove substances that could contaminate the results:

1. The samples were first dry cleaned of any visible soil and trabecular bone using a scraping tool, a steel brush, and a Dremel©; and then further cleaned in distilled water with an ultrasonicator.
2. The samples were dried in an oven at 60 degrees Celsius for 24 hours.
3. Each sample was ground using a ceramic mortar and pestle into a fine powder. Using a graduated sieve, fragments of less than 180 microns were separated, and were then weighed out into 20-30 mg of dry bone and stored in a labelled 2ml plastic sample tube. The exact weight of each sample was recorded.
4. Using a volumetric pipette, 0.04 ml of 2% reagent bleach were added to each sample per milligram of bone. The samples were left to soak in the bleach for 72 hours.
5. After 72 hours, the samples were rinsed five times each with de-ionized water. This was done by pipetting out the bleach, adding water, centrifuging the samples, then pipetting out the water and repeating the process four more times.
6. Next, 0.1 M acetic acid was added in a ratio of 0.04 ml per sample. The samples were left to soak in the acid, covered with plastic wrap, for four hours.
7. After 4 hours, the samples were again rinsed with de-ionized water using the method described in Step 5.
8. Immediately following the final rinse, a Kimwipe was secured over the mouth of each tube using an elastic band, and the samples were placed in a freezer overnight.
9. Once frozen, the samples were placed in a freeze-drier for two days.
10. After two days, the samples were removed from the freeze-drier and capped tightly. They were weighed again, and then the carbonate yield was determined using the formula:

$$\text{Apatite Yield \%} = \frac{\text{(weight of treated sample)}}{\text{(weight of untreated sample)}} \times 100\%$$

11. Finally, the samples were tightly capped and shipped to Light Stable Isotope Mass Spec Lab at the University of Florida to be run on a Finnigan-MAT 252 isotope ratio mass spectrometer with a Kiel III carbonate preparation device.

FTIR Processing

Each sample was also prepped for FTIR analysis in order to determine whether they had been subject to diagenetic alterations which could impact the integrity of the results (Shemesh 1990). FTIR preparation was carried out alongside carbonate preparation, and the cleaning process was identical to the methods described in Steps 1 and 2 of carbonate processing. As with the carbonate, samples being prepared for FTIR were also ground using a mortar and pestle (described in Step 3) and were processed through a graduated sieve. However, the FTIR samples must have a much smaller fragment size than carbonate sample—less than 63 microns. The dry bone powder was then weighed out into individual samples of 10-15 milligrams, and was stored in 2 ml plastic tubes.

The samples were then analyzed using the FTIR spectrometer at the University of Central Florida. Crystallinity Index and CO_3/PO_4 ratios were calculated from the resulting data in order to determine the level of preservation and diagenesis in each sample.

Procedure for Data Analysis

Since the samples from Yugüe date to the pre-collapse Terminal Formative period and the samples from Charco Redondo date to the post-collapse Early Classic period, comparing the $\delta^{18}O$ results from both sites will allow me to determine how or if regional population variation changed in the period following Terminal Formative collapse. There are several possible outcomes of $\delta^{18}O$ results, as shown in Figure 2 below.

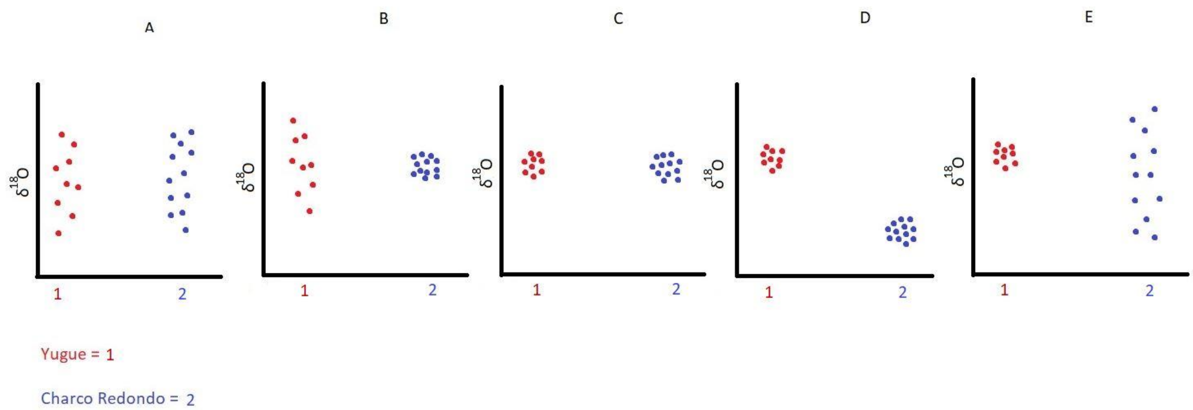

Figure 2: Different possible variations in $\delta^{18}O$ values

Each one of the five possible results shown in Figure 2 is a model for a different type of change in population mobility. Each of the dots represent the $\delta^{18}O$ value from a specific individual sample. Model A represents a scenario in which a high degree of variation exists in both sample sets from Yugüe and Charco Redondo, meaning that the individuals from both sites were consuming different water sources and may have come from different areas. Model B represents a scenario in which the population from Yugüe was likely consuming water from variable sources, while the population from Charco Redondo exhibits little variation in a water source—meaning that the Terminal Formative collapse may have caused people from around the region to migrate to Charco Redondo. Model C represents little to no change, and therefore little to no mobility occurring. Model D represents little variation within each population of Yugüe and Charco Redondo, but with variation between the two populations. Model E represents a scenario in which little variation between individual $\delta^{18}O$ values exists within the Yugüe population, but much variation exists between individuals from Charco Redondo—meaning that the collapse may have caused individuals to disperse across the region. My hypothesis most closely supports Model E, as I expect to find an increase in variation of $\delta^{18}O$ values within the population from Charco Redondo compared to that of Yugüe.

Chapter 4: Results

Sample Preservation

Skeletal remains from Coastal Oaxaca, and Mesoamerica in general, are often poorly preserved due to the hot, moist, tropical climate and hard, alkaline soil (Rumberger 2016). The soil of the lower Rio Verde Valley is relatively neutral (Sarah Barber, personal communication 2018), but the preservation was nevertheless poor and most of the osteological material was brittle, chalky, and weathered. One method for determining preservation of bone apatite is through calculating the apatite yield following chemical treatment, using the formula:

$$\frac{(\text{weight of treated sample})}{(\text{weight of untreated sample})} \times 100\%$$

In addition, since poor preservation can result in diagenetic alterations to the composition, an FTIR analysis was conducted on the samples to identify whether the $\delta^{13}C$ and $\delta^{18}O$ results could be considered accurate. This process produced a carbonate/phosphate ratio and a crystallinity index for each sample. The carbonate/phosphate (C/P) ratio is simply a measurement of the proportion of carbonate to phosphate in the sample. Since these are the primary substances that bone is composed of, this measurement allows us to confirm that the bone apatite has not become mineralized (Wright and Schwarcz 1996; Shemesh 1990). Crystallinity Index (CI) measures the amount of crystallization within the hydroxyapatitic structure of the bone, therefore allowing us to determine if diagenesis has affected the sample (Shemesh 1990). The results for the carbonate/phosphate ratios, crystallinity index, $\delta^{13}C$, and $\delta^{18}O$ values are summarized in Table 3 below.

Sample ID	Apatite Yield	Carbonate/Phosphate Ratio	Crystallinity Index	$\delta^{18}O$	$\delta^{18}O$
CR.2B	81.72%	0.184	3.094	-6.294	-7.995
CR.3B	80.67%	0.2	3.03	-5.886	-8.608
CR.5B	84.23%	0.157	3.371	-6.892	-8.681
CR.6B	83.63%	0.145	3.34	-5.979	-7.820
CR.8B	85.06%	0.175	3.128	-6.258	**-6.971**
CR.9B	84.80%	0.129	3.54	-7.562	-8.408
CR.10B	85.52%	0.165	3.291	-6.989	-8.451
CR.11B	81.57%	0.145	3.31	-4.397	-7.772
CR.11BB	82.95%	0.2	3.165	-3.887	-7.612
CR.12B	**75.51%**	0.223	**2.935**	-5.342	-8.413
CR.13B	83.19%	0.2	3.165	-6.097	-7.996
CR.14B	82.68%	0.152	3.348	-7.453	-8.502
CR.15B	84.53%	0.114	3.566	-7.083	-8.191
YG.2B	84.42%	0.092	**4.041**	-8.064	**-9.618**
YG.3B	84.85%	0.198	3.148	-5.252	-8.406
YG.4B	81.16%	0.148	3.399	-6.439	-8.138
YG.5B	87.60%	0.13	**3.929**	-8.400	**-10.044**
YG.6B	85.58%	0.079	**3.961**	-6.828	-8.871
YG.7BB	80.64%	0.184	3.121	-4.726	-7.589
YG.10B	87.50%	0.167	3.422	-7.524	-8.922
YG.11B	84.90%	0.158	3.294	-5.736	-7.982
YG.14B	81.12%	0.18	3.11	-6.619	-8.389

Table 3: Summary of apatite yield, carbonate/phosphate ratios, crystallinity index, $\delta^{13}C$, and $\delta^{18}O$ for each sample; unusual values are in bold.

With the exception of B31 I31 (CR.12B), all samples produced acceptable yields of over 80%, suggesting that the apatite samples were relatively well preserved. On average, the samples from Yugüe produced higher yields than those collected from Charco Redondo, indicating that environmental conditions at Yugüe may have been more suitable to bone preservation.

If the crystallinity index (CI) is not within the range of 3 to 3.6, then recrystallization has likely occurred due to diagenesis, and the oxygen and carbon isotope values may not be accurate (Shemesh 1990). It should be noted that sample B17 I19 (YG.7B) exhibited a particularly high CI (over 6.0), meaning that the values were clearly compromised. Due to the time constraints of this study, I have therefore removed it from the sample set. B31 I31 (CR.12B) shows a slightly low CI, while B8 I8 (YG.2B), B12 I13 (YG.5B), and B14 I16 (YG.6B) all show signs of possible recrystallization; the isotope results of these samples may therefore be inaccurate and should be taken with a grain of salt.

In order to further check for signs of diagenesis, I also tested for statistical relationships between crystallinity index and carbonate/phosphate ratios, $\delta^{13}C$ values, and $\delta^{18}O$ values separately for the Yugüe samples and Charco Redondo samples. Typically, if a trend is discovered, it can be assumed that any one of the result sets could be inaccurate.

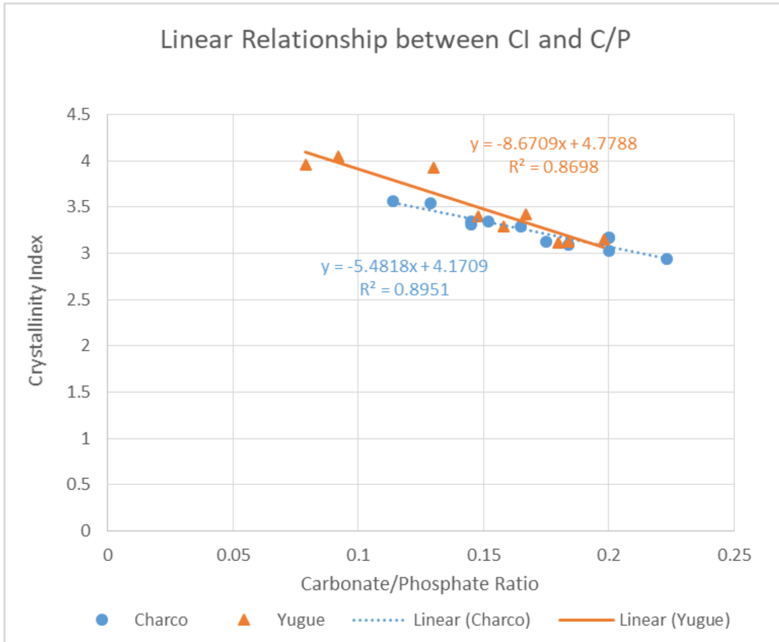

Figure 3: Data plot showing linear trend line and formula for CI and C/P

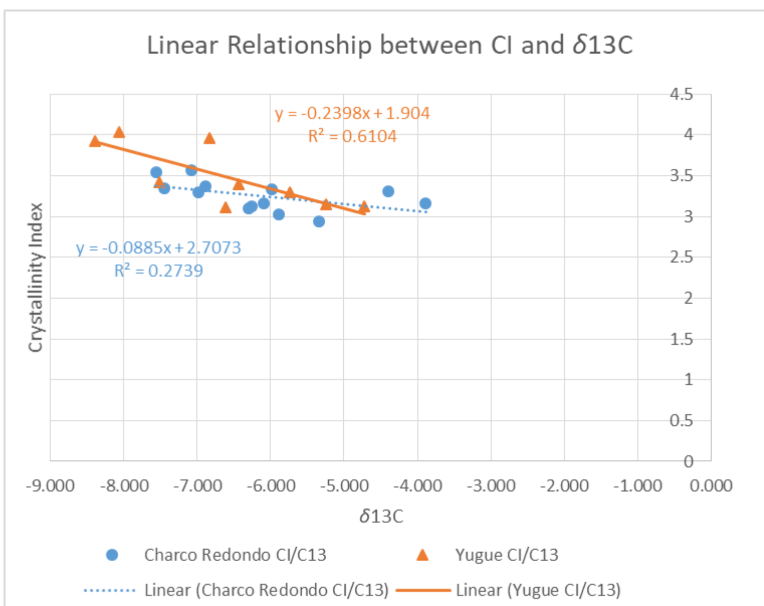

Figure 4: Data plot showing linear trend line and formula for CI and $\delta^{13}C$

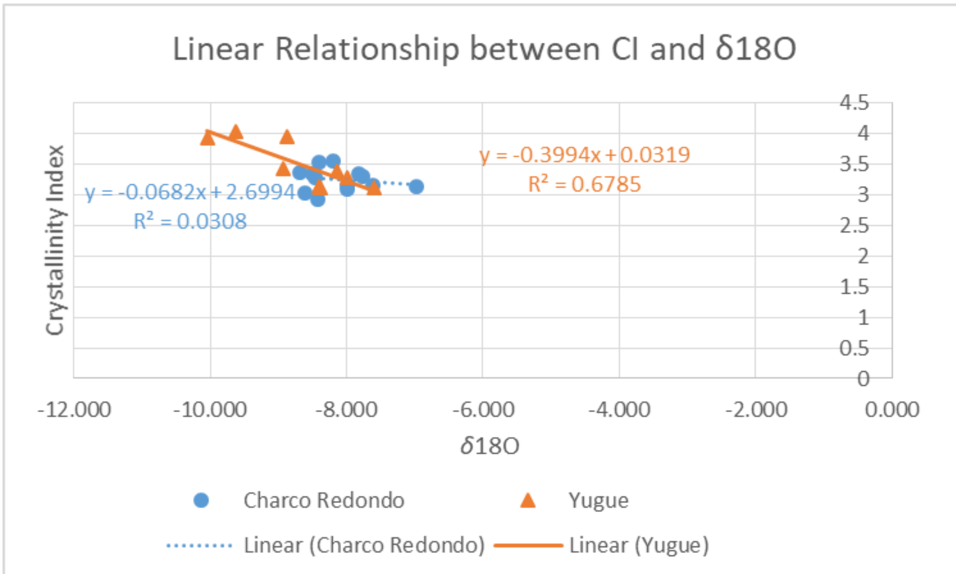

Figure 5: Data plot showing linear trend line and formula between Crystallinity Index and δ^{18}O

As seen in Figures 3-5, no significant linear relationship exists between crystallinity index and carbonate/phosphate ratios, δ^{13}C values, and δ^{18}O values. This supports the accuracy of the δ^{13}C values and δ^{18}O values.

δ^{13}C Results

As seen in Figure 6 below, the distribution of δ^{13}C values for both Yugüe and Charco Redondo are approximately normal, and the values from both sites show significant overlap. The average for Yugüe was -6.621 with a standard deviation of 1.173 and a range of 3.674. The average for Charco Redondo was -6.163 with a standard deviation of 1.067 and a range almost identical to Yugüe's at 3.675.

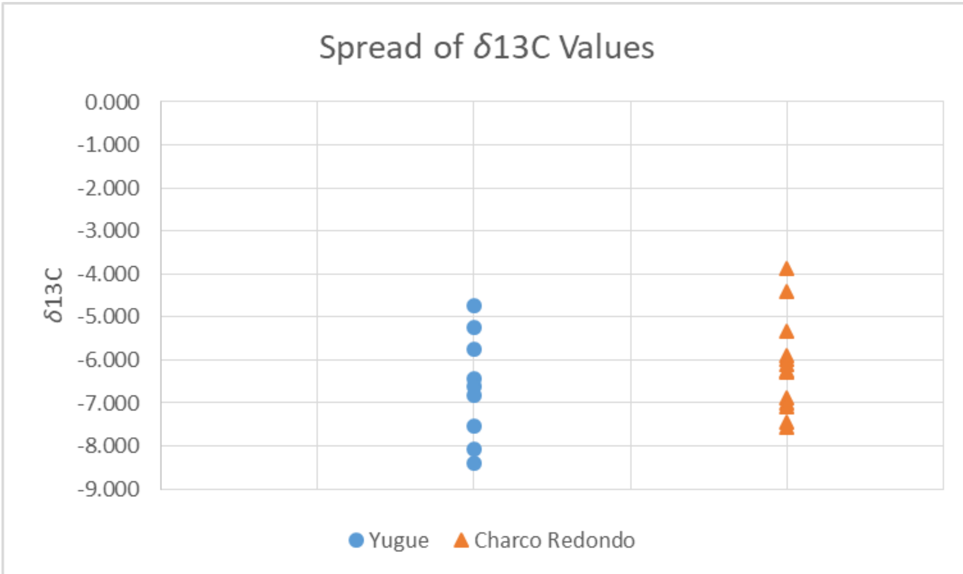

Figure 6: Data plot showing the distribution of $\delta^{13}C$ values

I also performed a non-parametric Mann-Whitey U test on the distributions of both Yugüe and Charco Redondo in order to compare the means. Because the sample set is quite small, a non-parametric test is more appropriate in this situation. According to Madrigal (2012), the Mann-Whitney U test assumes that the underlying level of measurement is continuous and that the samples are independent, and is expressed using the formula:

$$U_1 = (n_1)(n_2) + \frac{(n_1)(n_1+1)}{2} - \sum R_1, \text{ and } U_2 = (n_1)(n_2) - U_1$$

The test results produced a two-tailed significance of 0.48, which is far from statistical significance at the level of $p \leq 0.05$. This means that the $\delta^{13}C$ results from Yugüe and Charco Redondo are not significantly different.

δ^{18}O Results

The δ^{18}O results from Yugüe and Charco Redondo follow a similar pattern to the δ^{13}C results. As seen in Figure 7, there is significant overlap between the values from both Yugüe and Charco Redondo. The average for Yugüe is -8.662 with a standard deviation of 0.743 and a range of 2.455. The range is quite high due to a couple of outliers that are depleted in ^{18}O, and the distribution is therefore skewed to the left. The values from Charco Redondo have an average of -8.110 with a standard deviation of 0.464 and a range of 1.71. The majority of the values are clustered very closely together, with the exception of one outlier that is enriched in ^{18}O and causes the distribution to skew right.

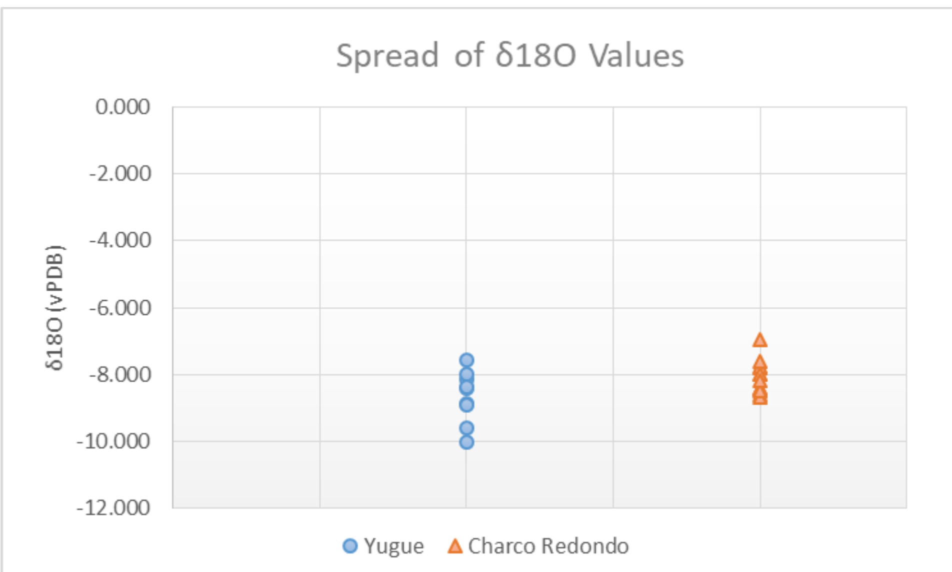

Figure 7: Data plot showing distribution of δ^{18}O results

As with the δ^{13}C values, I performed a Mann-Whitney U test on the sample sets from Yugüe and Charco Redondo in order to ascertain if the samples were derived from the same population by determining whether they were statistically different ($p \leq 0.05$). The test produced a two-tailed significance of 0.217, which is not considered significant.

Chapter 5: Discussion

Impact of Political Collapse on Human Mobility in Ancient Oaxaca

According to the results, there is significant overlap between the $\delta^{18}O$ values from Yugüe and those from Charco Redondo, meaning that the residents from both sites likely consumed water sources from the same geographic area. This is not surprising, since the sites are located along the same river only 6 km apart. Both sample sets show low variation in $\delta^{18}O$ values, but some of the Yugüe individuals were depleted in $\delta^{18}O$, while one outlier from Charco Redondo was enriched in $\delta^{18}O$. These may represent non-local values, suggesting that individuals YG.2B, YG.5B, and CR.8B could have migrated to their locality within the last ten to twenty years of their lives. Outliers are to be expected in the population, and these values are not representative of the inhabitants of Yugüe and Charco Redondo as a whole. Individuals living during the Terminal Formative and Early Classic period could have migrated across the region independently for any number of reasons—politics were likely not even factors in these individuals' decisions (assuming of course, that the outliers do represent non-locals). Because these cases are isolated incidences within my sample set, we can postulate these migrations are unrelated to broader socioeconomic impacts of the time such as collapse and political unrest. Interestingly, both Yugüe individuals who were depleted in $\delta^{18}O$ were female. In ancient Mesoamerica, it was common for women to marry men in different settlements in order to foster advantageous economic relationships (personal communication, Sarah Barber 2018). These women would migrate to their new home as late adolescents or early adults. YG.2B was aged at 40-50 at time of death, so her timeline does not support this theory. However, the age of YG.5B was estimated at about 20-25, supporting the theory that marriage mobility might account for her depleted $\delta^{18}O$ values. The sex of individual CR.8B is unknown, so it is more difficult to theorize on a reason for their enriched $\delta^{18}O$ values. It is interesting to note, however, that CR.8B was previously part of study undertaken during Michelle Butler's dissertation (Butler 2018) in which its stable strontium isotope values were analyzed to determine provenience. According to the strontium results, CR.8B appeared to be non-local, further supporting the oxygen isotope results from this study.

Overall, the $\delta^{18}O$ results from both populations exhibit very low variation between individuals in the same sample set, supporting a model for little to no population mobility both preceding the Terminal Formative political collapse and following it. Moreover, there is no significant difference in the mean from Terminal Formative period Yugüe and Early Classic period Charco Redondo. This suggests that the Terminal Formative collapse did not significantly affect mobility in the lower Rio Verde Valley. I found this surprising, given that the majority of literature surrounding political collapse lists 'site abandonment' (i.e. population mobility) as a typical consequence. I thus reject my original hypothesis that the isotopic evidence would support a model for intraregional population mobility following the Terminal Formative political collapse. These individuals lived during a time of political decentralization and instability, and they remained close to their geographic origin rather than migrating to a new area. I believe this speaks strongly to human nature in the face of change—in general, people seek familiarity over the unknown. Even as their central government collapsed and the authority which governed their polity was redistributed into regional centers, the inhabitants of the Rio Verde Valley remained close to their birthplaces.

Another possible interpretation is that central political authority in the Rio Verde Valley simply wasn't a significant factor in the everyday lives of regional groups in the first place, and therefore the political collapse at the end of the Terminal Formative period had little impact on the populations of periphery settlements like Yugüe and Charco Redondo. This hypothesis is supported by Joyce and Barber's 2015 discussion on *Ensoulment, Entrapment, and Political Centralization.* Joyce and Barber assert that social identity in the lower Rio Verde Valley was strongly tied to local community, and the concept of community was reinforced in part through burying the bones of ancestors and ceremonial offerings in public structures. To the residents of local communities, these remains and offerings represented a highly spiritual and emotional bond to the place where they were buried, essentially entrapping them within their communities. Residents were thus more likely to adhere to the authority of local community leaders. The centralized political authority at Rio Viejo, despite conscripting outlying communities for public building projects, simply could not overcome the loyalty people felt towards the communities of their ancestors. The already tenuous authority could not be maintained for long in these conditions, and that may have contributed to the eventual political collapse. This point is further reiterated in Barber and Joyce's *Polity Produced and Community Consumed* (2007), where they emphasize the importance of local elites. Local leaders followed community tradition and may have utilized their local status to retain authority independent of the polity's central authority. If local authority was indeed far more influential than the centralized government, then it can be assumed that a political collapse would not affect outlying communities enough to prompt populations to migrate. Furthermore, the spiritual ties that people had to the resting places of their ancestors would have been a major reason for people to stay, and residents would have been much more reluctant to leave a community if their family's remains were entrapped within a public communal structure.

Although the $\delta^{13}C$ values are not relevant to the context of this research project since they relate to diet rather than mobility, I will review the data for the purpose of future research endeavors. In both sample sets, the $\delta^{13}C$ values exhibit very little variation between individuals, indicating that residents of Yugüe and Charco Redondo followed similar diets to their fellow community members. Moreover, the significant overlap in values from Yugüe and Charco Redondo indicates that Yugüe residents were consuming more or less the same foods during the Terminal Formative period that Charco Redondo residents were consuming a few generations later during the Early Classic period. This is to be expected, since the sites are very close geographically and temporally, and the environment did not change significantly during that time frame. Moreover, this political collapse likely had no effect on diet.

Modern Impacts of Political and Social Change on Population Mobility

As discussed in the introduction, every complex society in history has experienced a political collapse (Tainter 1988). This rule holds even in modern times, and perhaps the findings from this project can be applied to help us better understand some of the varying ways in which modern populations might respond, at least in terms of mobility, to a political collapse.

The political climate in America may seem precarious at times, but the United States is not likely to face a true political collapse anytime soon. In fact, most Western countries have relatively stable centralized forms of authority, and thus are in no danger of collapse. The true threat of political collapse hangs over regions of the world like Africa, which is still greatly affected by historic European colonization in that many country's borders were established without taking original ethnic and cultural boundaries into consideration. Political authority therefore often has difficulties overcoming cultural loyalties, and governments often have a tenuous hold on regional communities (Zartman 1995; Rotberg 2004). If a political collapse occurs in the modern day, how might people respond in terms of mobility?

Of course, there are factors that differentiate modern situations of collapse from the one in Ancient Oaxaca. For example, the collapse in the lower Rio Verde Valley did not involve violent conflict, but modern instances of political collapse in the regions discussed above might. If this were the case, people would respond much differently than the residents of the lower Rio Verde. They would likely attempt to migrate away from the conflict, as we have seen very recently with the crisis in Syria prompting a mass emigration (Kingsley 2015). Another factor to consider is the increased access to transportation technology that we have today—perhaps if the residents of the lower Rio Verde had had access to high-speed trains and cars, they would have chosen to leave. However, even though the situations are vastly different, the findings from this study may still provide a window of insight into how populations respond to political change. If there is no major push, like violence or conflict, humans will often choose to stay in the community they are familiar with, to follow the leaders who share their local values, and to remain near the resting places of their families.

Chapter 6: Conclusion

According to past literature on political collapse as a process, as well as collapse within ancient Mesoamerica, I originally expected the isotopic evidence from the $\delta^{18}O$ values to support a model for intra-regional mobility following the political collapse at the end of the Terminal Formative period in the lower Rio Verde Valley. Instead, I was able to reject this hypothesis when the data revealed extremely low variation in the distribution of $\delta^{18}O$ values and no statistically significant difference between the mean values from the pre-collapse site of Yugüe and the post-collapse site of Charco Redondo. These results support a model in which little to no mobility was present in either population, and the political collapse had no effect on mobility patterns. The existence of a few outliers suggests that some of the excavated individuals may have been non-local, but these were likely isolated cases that represented circumstances such as marriage or trade.

The lack of mobility may be explained by a tendency for residents of local communities to leave the remains of ancestors and ritual offerings in public structures, thus creating an environment that tied people more securely to their local community (Joyce and Barber 2015). Furthermore, localized leadership may have held more authority in communities than the centralized authority of Rio Viejo. Thus, when that central political authority collapsed, the power that regional centers already held simply grew, and local communities were scarcely affected (Barber and Joyce 2007).

When considering the tenuous modern political climate of regions in the world such as Africa and Central Asia, we must think about how a political collapse can affect contemporary human populations. Even though modern situations differ dramatically from the political collapse in Ancient Oaxaca, humans may still be tied to the places they are familiar with. The findings from this study provide valuable insight into how human migration patterns correspond with political changes, both in the archaeological record of past civilizations and in modern societies of a rapidly changing global political sphere.

As previously stated in Chapter 2, stable isotopic research in Mesoamerica, and Oaxaca in particular, is not common. Stable isotope analysis is a fantastic tool at the disposal of the bioarchaeologist, and it should be utilized more extensively in this region to help answer questions about diet and mobility. This study in particular lent more information to our currently limited, but growing, understanding of the Terminal Formative period political collapse and how it affected the residents of the lower Rio Verde Valley. In order to expand upon this study, future research should focus on selecting a larger sample set from post-collapse and pre-collapse populations, so as to provide a more accurate picture of the mobility patterns. Water samples should also be collected from the Rio Verde in order to obtain baseline $\delta^{18}O$ values from which to compare the values of the remains. In addition, this study only analyzed the stable isotopes in bone carbonate. Since sufficient material is left over, future researchers may choose to attempt collagen extraction from these samples in order to analyze the carbon and nitrogen isotopes as they relate to diet within these populations. Furthermore, it would be extremely pertinent to obtain the teeth from these individuals and conduct an isotopic analysis of both the enamel and dentin. The dentin would act in the same way as bone collagen in that it relates to diet. However, teeth represent diet during childhood rather than the last ten years of life (Wright and Schwarcz 1999). Oxygen isotopes could be analyzed from the tooth enamel, providing a data set that relates to childhood which could then be compared to the bone apatite data sets that resulted from this study. This would allow us to determine whether individuals had migrated within their own lifetime, and would give us an even clearer understanding of how population mobility is related to the Terminal Formative collapse.

References Cited

Ambrose, Stanley H. and John Krigbaum.
2003 Bone Chemistry and bioarchaeology. *Journal of Anthropological Archaeology* 22(3):193-199.

Barber, Sarah B.
2005 Heterogeneity, identity, and complexity: negotiating status and authority in Terminal Formative Coastal Oaxaca. PhD Dissertation, Department of Anthropology, Graduate School of the University of Colorado, Boulder, Colorado.

Barber, Sarah B.
2013 Defining community and status at outlying sites during the Terminal Formative period. In *Polity and Ecology in Formative Period Coastal Oaxaca*, edited by Arthur A. Joyce, pp. 165-190, University Press of Colorado, Boulder.

Barber, Sarah B. and Arthur A. Joyce.
2007 Polity produced and community consumed: negotiating political centralization through ritual in the lower Rio Verde Valley, Oaxaca. In *Mesoamerican Ritual Economy Archaeological and Ethnological Perspectives*, edited by E. Christian Wells and Karla L. Davis-Salazar, pp. 221-244, University Press of Colorado.

Bender, Margaret M.
1968 Mass spectrometric studies of carbon 13 variations in corn and other grasses. *Radiocarbon* 10(2):468-472.

Butler, Michelle M.
2018 Early Classic Social Transformations: Identity, Community, and Authority at Charco Redondo, Oaxaca, Mexico. PhD Dissertation, University of California, Riverside.

Coplen, Tyler B.
1994 Reporting of stable hydrogen, carbon and oxygen isotopic abundances. *Pure and Applied Chemistry* 66:271-276.

Dansgaard, Willi.
1964 Stable isotopes in precipitation. *Tellus* 16:436–468.

DeNiro, Michael J.
1987 Stable isotopy and archaeology. *American Scientist* 75(2):182-191.

Diehl, Richard A.
1989 A shadow of its former self: Teotihuacan during the Coyotlatelco period. In *Mesoamerica after the decline of Teotihuacan A.D. 700—900*, Edited by Richard A. Diehl and Janet Catherine Berlo. Dumbarton Oaks Trustees for Harvard University, Washington, D.C.

Epstein, Samuel and Toshiko K. Mayeda.
1953 Variation of δ^{18}O content of water from natural sources. *Geochimica Cosmochimica.* Acta 4: 213-224

Fry, Brian
2006 *Stable isotope ecology*. Springer-Verlag New York.

Grove, David C.
1988 *Archaeological Investigations on the Pacific Coast of Oaxaca, Mexico,* 1986, Report submitted to the National Geographic Society, Washington, DC.

Grunenwald, Anne; Christine Keyser; Anne-Marie Sautereau, Eric Crubezy, Bertrand Ludes, and Christophe Drouet.
2014 Revisiting carbonate quantification in apatite (bio) minerals: a validated FTIR methodology. *Journal of Archaeological Science* 49:134–141

Hedges, Joshua E.M., Rhiannon E. Stevens, and Paul L. Kock.
2005 Isotopes in bones and teeth. In *Isotopes in Paleoenvironmental Research*, edited by Melanie J. Leng. pp. 117-145. Springer, Netherlands.

Hedges, Robert E., John G. Clement, David L. Thomas, and Tamsin C. O'Connell.
2007 Collagen turnover in the adult femoral mid-shaft: modeled from anthropogenic radiocarbon tracer measurements. *American Journal of Physical Anthropology,* 133(2):808-816.

Hepp, Guy D., Paul A. Sandberg, and Jose Aguilar.
2017 Death on the early formative Oaxaca Coast: the human remains of La Consentida. *Journal of Archaeological Science* 13:703-711.

Josserand, Kathryn J., Marcus Winter, and Nicholas Hopkins, Editors.
1984 *Essays in Otomanguean culture history*. Vanderbilt University publications in Anthropology 31. Vanderbilt University, Nasheville, TN.

Joyce, Arthur A.
1991a Formative period occupation in the lower Rio Verde Valley, Oaxaca, Mexico: interregional interaction and social change. PhD Dissertation, Rutgers University.

2010 *Mixtecs, Zapotecs, and Chatinos: Ancient Peoples of Southern Mexico.* Chichester, United Kingdom, Wiley-Blackwell.

Joyce, Arthur A.
Joyce, Arthur A., Marcus Winter, and Raymond G. Mueller.

1998 *Arquología de la costa de Oaxaca: Asentamientos del periodo formativo en el valle del Río Verde inferior*. Estudios de Antropología e Historia No. 40 Centro INAH Oaxaca, Oaxaca, Mexico.

Joyce, Arthur A. and Sarah B. Barber.
2015 Ensoulment, entrapment, and political centralization: a comparative study of religion and politics in later formative Oaxaca. *Current Anthropology*, 15:819-847.

Joyce, Arthur A., and Raymond G. Mueller.
2010 The social impact of anthropogenic landscape modification in the Río Verde drainage basin, Oaxaca, Mexico. *Geoarchaeology, 7*:503-526.

Joyce, Arthur A., and Raymond G. Mueller.
1997 Prehispanic human ecology of the Río Verde drainage basin, Mexico. *World Archaeology*. 29:75-94.

Katzenberg, Anne M.
2008 Stable isotope analysis: A tool for studying past diet, demography, and life history. In *Biological Anthropology of the Human Skeleton, 2nd edition*, edited by M. Anne Katzenberg and Shelley R. Saunders. John Wiley & Sons INC, New Jersey.

Kingsley, Patrick.
2015 "Over a Million Migrants and Refugees Have Reached Europe This Year, Says IOM." *The Guardian*, Guardian News and Media. Accessed May 25th, 2018.

Knudson, Kelly J., Christina Torres-Rouff, and Christopher Stojanowski.
2015 Investigating human responses to political and environmental change through paleodiet and paleomobility. *American Journal of Physical Anthropology*, 157:179–201.

Lambert, Joseph B.
1997 *Traces of the past: unraveling the secrets of archaeology through chemistry*. Perseus Publishing, Cambridge.

Madrigal, Lorena.
2012 *Statistics for Anthropology (2nd ed.)*. Cambridge: Cambridge University Press.

Mayes, Arion and Arthur A. Joyce.
2017 The bioarchaeology of the Cerro de la Cruz cemetery, Oaxaca, Mexico. *Journal of Archaeological Science*: 13:712-718.

Rotberg, Robert I.
2004 The failure and collapse of nation-states: breakdown, prevention, and repair. In *When States Fail*. Edited by Robert I. Rotberg, Princeton: Princeton University Press.

Rumberger, Jacklyn D.
2016 Diet and migration in Coastal Oaxaca: Identifying effects of political and social collapse through the utilization of stable isotope analysis. Master's thesis, Department of Anthropology, University of Central Florida, Orlando, Florida.

Schwartz, Glenn M., and John J. Nichols, Editors.
2010 *After collapse: the regeneration of complex societies*. Tucson: University of Arizona Press.

Sharp, Zachary.
2007 *Principles of stable isotope geochemistry*. Upper Saddle River, NJ: Pearson Education.

Shemesh, Aldo.
1990 Crystallinity and diagenesis of sedimentary apatites. *Geochimica et Cosmochimica Acta,* 54(9):2433-2438.

Tainter, Joseph A.
2017 *The collapse of complex societies*. Cambridge University Press, United Kingdom.

Warinner, Christina, Nelly R. Garcia, and Noreen T. Tuross.
2013 Maize, beans and the floral isotopic diversity of highland Oaxaca, Mexico. *Journal of Archaeological Science*. 40:868-873.

White, Christine D., Michael W. Spence, Hilary L. Q. Stuart-Williams, and Henry P. Schwarcz.
1998 Oxygen isotopes and the identification of geographical origins: The Valley of Oaxaca versus the Valley of Mexico. *Journal of Archaeological Science*. 25:643-655.

White, Christine D., Michael W. Spence, Fred J. Longstaffe, and Kimberly R. Law.
2004 Demography and ethnic continuity in the Tlailotlacan enclave of Teotihuacan: the evidence from stable oxygen isotopes. *Journal of Anthropological Archaeology*, 23:385-403.

White, Christine D., Michel W. Spence, and Fred J. Longstaffe.
2011 The Teotihuacan Dream: An isotopic study of economic organization and immigration. In *The "Complete Archaeologist" Papers* in Honour of Michael Spence. Edited by Ellis, C., Ferris, N., Timmins, P., and White, C. Occasional Publications of the London Chapter, Ontario Archaeological Society, No. 9 (co-published as *Journal Ontario Archaeology,* Volumes 85 to 88,. pp. 279-297.

Wickman, Frans E.
1952 Variations in the relative abundance of the carbon isotopes in plants. *Geochimica et Cosmochimica* Acta 2:243-254.

Wright, Lori E. and Henry P. Schwarcz

1999 Correspondence between stable carbon, oxygen and nitrogen isotopes in human tooth enamel and dentine: infant diets at Kaminaljuyu. *Journal of Archaeological Science* 26:1159-1170.

Zartman, Ira William
1995 Introduction: Posting the Problem of State Collapse. In *Collapsed States: The Disintegration and Restoration of Legitimate Authority*. Edited by Ira William Zartman. Lynne Rienner Publishers, Inc., Boulder.