# PALEOCLIMATE RECONSTRUCTION USING ISOTOPIC ANALYSIS OF TROPICAL BIVALVES FROM THE PIGEON CREEK ARCHAEOLOGICAL SITE,

#### SAN SALVADOR ISLAND, BAHAMAS

by

#### REBECCA J. CERAJEWSKI

#### (Under the direction of Christopher S. Romanek)

#### ABSTRACT

This research investigates the paleotemperatures of the northeastern Bahamas by comparing oxygen isotope records constructed from modern and archeological specimens of *Codakia orbicularis*, collected on San Salvador, Bahamas. The stable isotope profiles for modern *Codakia* accurately recorded sea surface temperatures measured at Pigeon Creek lagoon. The  $\delta^{18}$ O values for the modern specimens ranged from -1.5 to +0.8% and averaged -0.2%, while  $\delta^{18}$ O values for the archeological specimens ranged from -1.6 to +1.9% and averaged +0.2%. The modern and the archaeological groups are isotopically distinct suggesting that sea surface temperature or the  $\delta^{18}$ O of surface waters differed between AD 1450 and today. The archaeological specimens had higher maximum  $\delta^{18}$ O values, which could reflect a cooler and/or drier climate in the past. In addition, the range of  $\delta^{18}$ O values for the archaeological samples is larger than the modern samples, suggesting that temperatures may have varied more widely on a seasonal temporal scale.

INDEX WORDS: Paleoclimate, Oxygen isotopes, Carbon isotopes, Sclerochronology, *Codakia orbicularis*, Pigeon Creek, San Salvador, Bahamas, Caribbean

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## **TABLE OF CONTENTS**

		Page
ACKNO	WLEDGEMENTS	iv
LIST OF	TABLES	vii
LIST OF	FIGURES	viii
CHAPTE	R	
1	INTRODUCTION	1
	Research Questions	3
2	BACKGROUND	4
	Codakia orbicularis	4
	Sclerochronology	10
	Stable Isotopes	14
3	METHODOLOGY	17
	Field Location	17
	Specimen Collection	
	Laboratory Methods	
	Data Analysis	
4	RESULTS	
	Water	
	Carbonate	
	Statistics	
5	DISCUSSION	
	Modeling	
	Sclerochronology and Stable Isotopes	
	Archaeological Significance	

	6	CONCLUSIONS	. 70
		Future Research	.71
REFERENCES			.73
APPENDICES		. 80	
	А	REPLICATES AND STANDARDS	. 81
	В	ISOTOPE DATA	. 85
	С	STATISTICS	. 98

## LIST OF TABLES

Table	Page
3.1	The difference between original data and replicates for Codakia samples. The
	average, standard deviation, maximum, and minimum (absolute) values for
	the differences in replicates are listed here. The complete list of replicate data
	is reported in Appendix A
4.1	Sea surface temperature, $\delta^{18}$ O, and $\delta^{13}$ C of water samples from San Salvador
	Island. Summer averages for south Pigeon Creek were computed using the
	values for the May-99 samples and the June-00 sample. Annual averages and
	weighted averages for south Pigeon Creek were computed using the values for
	May-99, June-00, and Jan-00
4.2	Monthly maximum and minimum sea surface temperatures (°C) determined
	from the monthly range of observed temperatures and historical records
4.3	The height of shell, the number of drilled samples, and the average,
	maximum, and minimum isotope values for each specimen
4.4	Results of the K-S test: D-values were less then the Critical D, thus the data
	were normally distributed
4.5	Isotope data were compiled into two groups: the modern and the
	archaeological. F-test of modern vs. archaeological group (Table 4.5. A). T-
	test for unequal variance of the modern vs. archaeological groups of data
	(Table 4.5. B)
5.1	The number of cycles found identified in the $\delta^{18}O$ record, the number of dark
	increments found on the shell surface, and the maximum height of each
	specimen

## LIST OF FIGURES

Figure	Page
2.1	General anatomy and life position of Codakia orbicularis. Symbols: A,
	auricle; AA, anterior adductor muscle; D, right demibranch of gill; F, foot;
	IML, inner mantle lobe; IT, inhalent tube; K, kidney; L, ligament; MC, mantle
	cavity; MG, mantle gills; ML, middle mantle lobe; OL, outer mantle lobe; PA,
	posterior adductor muscle; PL, pallial line; R, rectum; SWI, sediment-water
	interface (modified from Jackson, 1973)5
2.2	Growth rate of Codakia orbicularis (reproduced from Berg and Alatalo,
	1984)9
2.3	Codakia orbicularis specimen, PCL-UN2, showing shell morphology. The
	ribs run parallel to the height of the shell, while the growth increments run
	perpendicular to the ribs from the umbo to the margin. Note the sampling
	points along growth increments (green arrow) 11
2.4	Photomicrograph of the microstructure of Codakia orbicularis in plane
	polarized light. Photo is 3.5 mm wide. The red arrows point to increments
	that had been removed for isotopic analysis. However, since the growth
	increments were point sampled, these highlighted increments in the thin
	section may or may not show the actual drilled pits. The bright green lines
	highlight some of the daily increments 12
3.1	San Salvador Island, showing location of Pigeon Creek and the Pigeon Creek
	archaeological site. Inset of the Bahama Islands, showing the locations of San
	Salvador and Lee Stocking Islands (Modified from Craton and Saunders,
	1992)

3.2	A. Photograph of the Pigeon Creek archaeological excavations viewed from
	the trail that leads up to the site. B. Photograph of Pigeon Creek viewed from
	the archaeological site at the top of the hill
3.3	Pigeon Creek showing the collection area for modern Codakia orbicularis.
	Live specimens were collected near the boat dock and the shells were
	collected in the area marked by the purple box (modified from Robinson and
	Davis, 1999)
3.4	Photograph of the area of Pigeon Creek where live specimens of Codakia
	orbicularis were collected
3.5	Underwater photograph showing a shell deposit, including Codakia
	orbicularis, at the bottom of the tidal channel in Pigeon Creek
4.1	"Envelope" of maximum and minimum sea surface temperatures. LSI = Lee
	Stocking Island
4.2	PCL-UN2: A. $\delta^{18}$ O values. Numbers represent approximate ages. Red
	squares identify "dark" increments and pink squares identify "disturbance"
	increments. Green diamonds are replicates values. B. $\delta^{13}C$ values. Boxes
	outline juvenile and adult growth phases
4.3	PCL-BO2: A. $\delta^{18}$ O values. Numbers represent approximate ages. Red
	squares identify "dark" increments and pink squares identify "disturbance"
	increments. Green diamonds are replicates values. B. $\delta^{13}C$ values. Boxes
	outline juvenile and adult growth phases
4.4	PCM-UN21: A. $\delta^{18}$ O values. Brackets identify cycles. Numbers represent
	approximate ages. Red squares identify "dark" increments and pink squares
	identify "disturbance" increments. Green diamonds are replicates values. B.
	$\delta^{13}$ C values. Boxes outline juvenile and adult growth phases
4.5	PCM-UN22: A. $\delta^{18}$ O values. Brackets identify cycles. Numbers represent
	approximate ages. Red squares identify "dark" increments and pink squares

ix

identify "disturbance" increments. Green diamonds are replicates values. B.
$\delta^{13}$ C values. Boxes outline juvenile and adult growth phases
PCA-6: A. $\delta^{18}$ O values. Brackets identify cycles. Numbers represent
approximate ages. Red squares identify "dark" increments and pink squares
identify "disturbance" increments. Green diamonds are replicates values. B.

4.6

- 5.1 Seasonal  $\delta^{18}O_{ar}$  equilibrium model for southern Pigeon Creek calculated from the Grossman and Ku (1986) paleotemperature equation, using the observed seasonal range in temperature for the Bahamian region (Table 4.2) and the average of winter and summer  $\delta^{18}O$  values for south Pigeon Creek water (Table 4.1; black lines). A second model for south Pigeon Creek (red lines) was calculated using the observed seasonal range in temperature for the Bahamian region (Table 4.2) and the average of the sum of summer  $\delta^{18}O$ values and the one winter  $\delta^{18}O$  value for south Pigeon Creek water (Table 4.1). A third model for south Pigeon Creek (blue lines) was calculated using

- 5.5 The three  $\delta^{18}$ O models for modern-day south Pigeon Creek compared to the models created to fit the range of archaeological data (Table 4.3). Model A (purple open squares) was created using the annual average of  $\delta^{18}O_{H2O}$  for Pigeon Creek (Table 4.1) and the minimum winter temperatures had to be decreased by 1.65°C to fit the range of the archaeological data. Model B

#### **CHAPTER 1**

#### **INTRODUCTION**

Climate fluctuates between warmer and cooler periods on scales of thousands to tens of years. For example, the Little Ice Age was a relatively short-term climatic fluctuation, but its effects can be seen globally. The Little Ice Age (~AD 1400-AD 1850) was characterized by a colder and more humid climate as a result of advancing mountain glaciers. The advancing mountain glaciers during Little Ice Age may have originated from a decrease in solar activity or an increase in volcanic activity, but these ideas are still being investigated. Occasional severely cold winters were another characteristic of the Little Ice Age (Seibold and Berger, 1996). These characteristics of the Little Ice Age have been found in fossils and sediments throughout North America, the Caribbean, Europe, and Asia (Druffel, 1982; Curtis and Hodell, 1993; Curtis et al., 1996; Keigwin, 1996; Campbell et al., 1998; Ingram et al., 1998; Watanabe et al, 2001).

For the time period of the Little Ice Age (~AD 1400-AD 1850), a highresolution paleoclimate record for the Bahamas is needed. Existing paleoclimate research for the Atlantic Ocean near the Bermuda Rise during the Little Ice Age suggest sea surface temperatures were about 1°C cooler than the modern (Keigwin, 1996). In the Caribbean, conditions may have been more humid after ~AD 1391 (Curtis et al., 1996). Additionally, Nyberg et al. (1999) suggested that during the time period of the Little Ice Age winter sea surface temperatures decreased while the seasonal variability increased for the northeastern Caribbean. A compilation of previous research has resulted in a low-resolution paleoclimate record for the time period of the Little Ice Age (~AD 1400-AD 1850) in the Caribbean region. This low-resolution paleoclimate model has temporal and spatial gaps in its data. In an effort to fill in these gaps, this study creates a high-resolution paleotemperature record at a Bahamian archaeological site for the beginning of the Little Ice Age, i.e. about AD 1440-1530.

Paleotemperature reconstruction is of particular interest to archaeologists studying the Pigeon Creek archaeological site on San Salvador Island, Bahamas. This information will help archaeologists reconstruct the lifestyles of the original inhabitants of the Bahamas, or the Lucayans. Site size is one of the phenomena being investigated at Pigeon Creek archaeological site. The archaeologists are trying to establish if the Pigeon Creek site is the result of repeated short-term occupations, or repeated occupations of large numbers of people. Additionally, the archaeologists are interested in whether these occupations are year-round or seasonal. Finally, the archaeologists are examining the response of the Lucayan population to changing climate. A population increase might be the result of cooler and wetter climate conditions (Berman and Gnivecki, 1995). A few degrees change in temperature can have a big impact in the life history strategies of the native people. Temperature changes can even alter basic forms of agriculture and even shift the availability of marine food sources.

Paleotemperatures were reconstructed using the oxygen isotope ratios obtained from the bivalve *Codakia orbicularis*, which is ubiquitous in a Pigeon Creek archaeological deposit and the modern Pigeon Creek lagoon on San Salvador. Sequential samples of carbonate from incremental growth lines were collected from the outer surface of *Codakia* shells from the umbo to the lip and isotopically analyzed. These  $\delta^{18}$ O data were then used to calculate paleotemperature of the water in which *Codakia* lived. Seasonality in the modern specimens showed that *Codakia orbicularis* is a viable indicator of marine temperatures, i.e. a valid temperature proxy. The carbon isotopic profiles were also examined to determine if seasonality could be observed and/or if there are shifts within the isotope records due to sexual maturity. By comparing the oxygen isotope analyses of modern and archaeological samples, paleotemperature was reconstructed for a period of occupation  $(380 \pm 40^{14} \text{C BP})$  on the Pigeon Creek archaeological site, San Salvador Island.

#### **Research Questions**

- 1) Does *Codakia orbicularis* precipitate its shell in oxygen isotopic equilibrium with the surrounding seawater?
- 2) Are the growth rates of modern and archaeological *Codakia*, estimated by seasonal cycles within the oxygen isotope records, similar to the growth rate computed by age-class determination for Berg and Alatalo (1984)?
- 3) Is there seasonality in the carbon isotopic profiles and are there shifts within these isotope records due to sexual maturity?
- 4) Do the dark increments in *Codakia orbicularis* shells represent the winter season, with more positive  $\delta^{18}$ O values, and do these winter breaks allow for the determination of age and season of capture?
- 5) Based on the  $\delta^{18}$ O records, do *Codakia orbicularis* shells from the Pigeon Creek archaeological site, or more specifically the midden in which they originated, represent a single harvesting event by the Lucayans, as suggested by Berman (2001)?
- 6) Does the range of  $\delta^{18}$ O values from the archaeological samples differ from the range of  $\delta^{18}$ O values from the modern specimens, suggesting that seasonal temperature fluctuations may have been different for the period of occupation on the archaeological site than today?

#### **CHAPTER 2**

#### BACKGROUND

#### Codakia orbicularis

#### Biology

#### General anatomy

The general anatomy and life position of the bivalve, *Codakia orbicularis* (Family Lucinidae) is shown in Figure 2.1. Rather than reiterate general molluscan biology, the differences in general anatomy between *Codakia orbicularis* and other mollusc species are discussed in this chapter.

*Codakia* have mantle gills that are unique to the Family Lucinidae. These mantle gills are described as "a varying number of ridged folds that stretch from the posterior end of the anterior adductor muscle backwards and downwards towards the siphons and the mantle edge" (Allen, 1958; p. 430). Allen (1958) hypothesized the function of the mantle gills to be respiratory, and if true, this would allow the clam a maximized surface for oxygen absorption. Reid and Brand (1986) concur with this hypothesis and suggest that the mantle gills may also be a site of sulfide absorption.

*Codakia orbicularis* possess an inhalent aperture rather than an inhalent siphon (Allen, 1958). *Codakia* makes use of an inhalent tube that was created by the foot as an intake of seawater. *Codakia* does possess an exhalent siphon (not shown on Figure 2.1) that retracts, turns inside out, and then lies in the suprabranchial cavity. This process is responsible for the lack of a pallial sinus. The exhalent siphon also extends to the same extent as the foot, or inhalent tube, nearly six times the size of the shell (Allen, 1958). The ability to form an anterior inhalent tube has resulted in the elongation of the anterior adductor muscle (Allen, 1958).

The long, vermiform foot forms the inhalent tube with the aid of a mucus-secreting



**Figure 2.1.** General anatomy and life position of *Codakia orbicularis*. Symbols: A, auricle; AA, anterior adductor muscle; D, right demibranch of gill; F, foot; IML, inner mantle lobe; IT, inhalent tube; K, kidney; L, ligament; MC, mantle cavity; MG, mantle gills; ML, middle mantle lobe; OL, outer mantle lobe; PA, posterior adductor muscle; PL, pallial line; R, rectum; SWI, sediment-water interface (modified from Jackson, 1973).

tip (see Figure 2.1; Allen, 1958). Along with creating the inhalent tube, the foot has burrowing and locomotion functions as well. The foot and the well-developed heel (not shown on Figure 2.1) burrow at an angle to the substratum and can be permanently positioned with an inhalent tube within 10 hours (Allen 1958). Once positioned within the substratum, *Codakia orbicularis* can not move up and down within the sediment column (Reid and Brand, 1986).

There is a general reduction in the size and ciliation of the gills compared to other bivalves, and *Codakia* only possesses an inner demibranch (Berg and Alatalo, 1984; Allen, 1958). In addition to the reduction of the gills, the palps, sorting mechanisms, and stomach are also reduced, which may be attributed to their dependence of symbiotic bacteria for nutrition (Allen, 1958).

#### Symbiotic Bacteria and Nutrition

Chemoautotrophic bacteria live symbiotically within the gill cells of *Codakia orbicularis* (Berg and Alatalo, 1984; Frenkiel and Mouëza, 1995). The bacteria, identified as gram-negative (Berg and Alatalo, 1984; Le Pennec et al., 1995), oxidize environmental hydrogen sulfide, reduce and fix carbon dioxide, and also generate reduced forms of nitrogen (Berg and Alatalo, 1984; Schweimanns and Felbeck, 1985). A source of nutrition for *Codakia*, bacterial metabolites are probably absorbed intracellularly by the host (Fiala-Medioni et al., 1994). Additionally, symbiotic bacteria are absorbed directly by the host, thus providing yet another likely source of nutrition (Fiala-Medioni et al., 1994; 1986; Gros, Frenkiel, and Mouëza, 1998).

Organic detritus and plankton are abundant in the *Thalassia* beds in which *Codakia orbicularis* thrives (Jackson, 1972). Even with this abundance of available nutrients, Berg and Alatalo (1984) suggest that symbiotic bacteria remain a more likely source of nutrition, and support this statement with the following evidence:

(1) The reduction in the digestive system probably does not allow the acceptance

of large particles of food, because large particles in the gut or feces were never found.

(2) Low  $\delta^{13}$ C in the soft body and gill tissues of *Codakia orbicularis* is consistent with bacteria as a food resource, but this does not completely dismiss the possibility of nutrition from organic detritus.

In support of Berg and Alatalo (1984), Schweimanns and Felbeck (1985) interpret the minimal digestive system as a result of the presence of symbiotic bacteria, which breaks down the nutrients for the clam. Furthermore, Le Pennec and Beninger (2000) suggest that *Codakia orbicularis* receives a continuous trophic input that may be attained through one source of nutrition (symbiotic bacteria) and/or several sources of nutrition (symbiotic bacteria, plankton, and organic detritus). The ultimate source of nutrition for *Codakia orbicularis* remains uncertain, but is most likely partaking in nutrients from its endosymbionts.

#### **Reproduction**

The reproductive cycle of *Codakia orbicularis* is not fully discussed here but rather, this section focuses upon sexual maturation and spawning as they effect growth rate. Gametic development begins in early spring and continues until most of the population is ripe in late summer to fall, with laboratory spawning occurring from May to October (Berg and Alatalo, 1984; Alatalo et al., 1984). The development of larvae presumably occurs in the same general habitat as adults (Berg and Alatalo, 1984). Inoculation of the symbiotic bacteria occurs at a postmetamorphic developmental stage (Berg and Alatalo, 1984; Gros et al., 1997). However, Gros et al. (1998) presently believe inoculation of the bacteria occurs independent of habitat, instead being environmentally transmitted from a free-living form to the new host (Gros et al., 1996; Gros et al., 1998).

#### Growth Rates

The growth rate of *Codakia orbicularis* was calculated using the von Bertalanffy growth equation using data from Gold Rock Creek and Crystal Beach, Grand Bahama Island by Berg and Alatalo (1984). Monthly collections of shells from both locations were delineated into annual size classes, and these data were input into the equation to produce growth curves for *Codakia* (Figure 2.2). During the process of calculating the growth curves, Berg and Alatalo (1984) determined that variation exists between individuals of *Codakia orbicularis*. They observed "sharp growth rings" or dark increments on the outer surface of the shell suggesting that growth is not continuous throughout the year. Alatalo (2000) later stated that while the dark increments could be correlated with seasonality. The random occurrence of dark increments is hypothesized to be the result of the continuous nutrition that *Codakia* received from its symbiotic bacteria (Alatalo, 2000).

Alternatively, Mitchell (1983) interpreted these dark increments as representing an annual break in shell growth (in winter) followed by one or more months of slow growth. Using sclerochronological techniques, Mitchell (1983) suggested that the ridge and trough growth increments found on the surface of the shell represent deposition of shell material during spring and neap tide, respectively. Together, two sets of the ridge and trough growth increments would represent approximately one month of growth (Mitchell, 1983).

#### Ecology

*Codakia orbicularis* is found from Florida to the West Indies (Abbott and Morris, 1995). *Codakia* is most common in tropical and subtropical waters, usually dwelling in shallow depths but occasionally as deep as 87 m (Jackson, 1973). *Codakia orbicularis* commonly lives within the roots of *Thalassia* about 4-12 cm below the sediment-water interface (Berg and Alatalo, 1981). *Codakia* are also found in the mud banks of creeks,



**Figure 2.2.** Growth rate of *Codakia orbicularis* (reproduced from Berg and Alatalo, 1984).

both intertidally and to depths of 2 m (Berg and Alatalo, 1982). Although *Codakia* can live in sandy and muddy sediments, they do not reach the size of their *Thalassia*-dwelling counterparts (Schweimanns and Felbeck, 1985).

The *Thalassia* beds have high  $H_2S$  concentrations and a relatively low pH (Jackson, 1972). Even in these sulfidic conditions, *Codakia* thrives (Allen, 1958) but in a patchy distribution (Berg and Alatalo, 1984). *Codakia orbicularis* can also tolerate stagnant conditions (no oxygen, hydrogen sulfide present) for up to 11.75 days under laboratory conditions (Jackson, 1973). Additional laboratory tests indicated that the upper limit of tolerance for water temperature (30 minutes) is ~36.4°C with adults (>4 cm) being more heat tolerant than juveniles (<1 cm; Jackson, 1973).

Jackson (1973) also demonstrated in the laboratory that *Codakia orbicularis* could permanently tolerate salinities as low as 16-18‰. A minimum field salinity for the occurrence of *Codakia* is ~28‰ in Jamaica (Jackson, 1972). Extensive *Thalassia* growth is limited to areas usually around normal seawater salinity, but readings of 20-25‰ are common in *Thalassia* beds around mangroves (Jackson, 1973).

#### Shell

The outer shell of *Codakia orbicularis* has radiating ribs from the umbo that are crossed by elevated growth lines, giving a cross-hatched appearance, or cancellate pattern (Figure 2.3; Abbott and Morris, 1995). The mineralogy of the shell is entirely aragonitic and contains three microstructures: 1) outer composite prismatic, 2) middle crossed-lamellar, and 3) inner complex cross-lamellar (Figure 2.4; Taylor et al., 1973).

#### Sclerochronology

Sclerochronology, or the study of periodic features in the skeletal portions of animals, can be used in the determination of age and growth rate (Jones, 1988). Analogous to tree rings, the alternating light and dark growth increments observed in



**Figure 2.3.** *Codakia orbicularis* specimen, PCL-UN2, showing shell morphology. The ribs run parallel to the height of the shell, while the growth increments run perpendicular to the ribs from the umbo to the margin. Note the sampling points along growth increments (green arrow).



**Figure 2.4.** Photomicrograph of the microstructure of *Codakia orbicularis* in plane polarized light. Photo is 3.5 mm wide. The red arrows point to increments that had been removed for isotopic analysis. However, since the growth increments were point sampled, these highlighted increments in the thin section may or may not show the actual drilled pits. The bright green lines highlight some of the daily increments.

mollusc shells mark time as the animal ages. These alternating growth increments are light and dark in hand sample (reflected light), but in thin section (transmitted light) they are opaque and translucent, respectively (Jones, 1980b; Jones et al., 1989). The dark and light coloration is attributed to the relative abundance of organic matter within the shell (Lutz and Rhoads, 1980). Additionally, some dark increments (in hand sample) are relatively soft as well as organic rich. It is possible that these increments are the result of partial dissolution (Lutz and Rhoads, 1980). Higher magnification is required to see daily growth increments (Figure 2.4).

Growth increments are shown to represent a growth history of a mollusc, analogous to tree rings, and may have a basis in seasonal and/or environmental change (Pannella and MacClintock, 1968; Krantz et al., 1987; Jones et al., 1989). Light and dark increments were originally thought to represent summer and winter seasons and/or sudden salinity and temperature changes (Pannella and MacClintock, 1968; Jones, 1980b; Krantz et al., 1987; Jones et al., 1989). However, as research expanded to include species from more diverse geographical regions, molluscs from warmer climates were observed to deposit dark increments in the summer season, rather than winter (Clark, 1979; Peterson et al., 1983; Fritz and Haven, 1983; Grizzle and Lutz, 1988; Jones et al., 1990; Jones and Quitmyer, 1996). In addition to water temperature, the rate of shell growth or even growth cessation may be dependent upon extreme environmental conditions (Epstein and Lowenstam, 1953; Clark, 1979; Krantz et al., 1987). Mollusc species (Krantz et al., 1984) vary as to what controls the deposition of the light and dark increments. Summarily, specific growth increments that can be correlated with an annual event are helpful in determining age and growth rate for modern and fossil molluscs (Jones, 1980b; Thompson et al., 1980; Krantz et al., 1984), and even the season of death (Jones, 1980b). However, some dark increments cannot be correlated with any periodic event and may be the result of a minor environmental disturbance, causing the animal to disrupt its shell deposition for a short period of time (Jones et al., 1989). Ultimately, light and dark

increments aren't necessarily deposited in a particular season, and some increments are formed as a result of transient events.

#### **Stable Isotopes**

Stable isotopic records of molluscan shells may record seasonal fluctuations that correlate to the temperature of the surrounding water (Killingley and Berger, 1979; Erlenkeuser and Wefer, 1981; Donner and Nord, 1986; Romanek et al., 1987; Romanek and Grossman, 1989). Environmental changes, such as water depth, can effect the isotopic records of molluscs (Krantz et al., 1987; Romanek and Grossman, 1989). The isotopic effect with water depth is probably the result of changes in the thermocline but may also be attributed to nutrient concentrations (Williams et al., 1982; Arthur et al., 1983). Extreme sea surface temperatures can effect the isotopic record depending upon the tolerance and biology of the mollusc. An extreme sea surface temperature may be beyond the tolerance of a mollusc, inducing shell cessation and consequently causing the corresponding  $\delta^{18}$ O value to be missing from the shell's isotopic record (Erlenkeuser and Wefer, 1981; Romanek et al., 1987; Romanek and Grossman, 1989).

In addition to extreme sea surface temperatures, microenvironmental changes might effect the seasonality in the isotopic records of molluscs. Chivas et al. (1983) demonstrated that two different molluscs living in the same habitat could record similar oxygen isotopic records to the temperature record. However, Romanek and Grossman (1989) demonstrated differences in isotopic records of co-inhabitants and suggested the difference might be attributed to restricted environments. Finally, infaunal molluscs may record altered seasonality if the incorporation of isotopically light pore-water bicarbonate occurs during shell formation (Krantz et al., 1987).

Molluscs may contain symbionts that can effect the  $\delta^{18}$ O and  $\delta^{13}$ C of the carbonate shell. Jones et al. (1986) showed a depletion in the  $\delta^{13}$ C in *Tridacna maxima* and determined that the mollusc incorporated excess metabolic CO<sub>2</sub> into the shell from its

photosymbiotic zooxanthellae. However, the photosymbionts in *Tridacna maxima* do not appear to effect the  $\delta^{18}$ O of its shell carbonate (Jones et al., 1986; Romanek et al., 1987; Romanek and Grossman, 1989).

#### Sclerochronology and Stable Isotopes

The subjectivity of sclerochronology can be resolved by pairing it with stable isotopic analysis. For example, Krantz et al. (1984) discovered a discrepancy between the sclerochronology-determined age and the isotopically-determined age of a mollusc. The number of annual increments determined by sclerochronology did not correspond well with the number of cycles determined from the isotopic profiles (Krantz et al., 1984). As a result, current research uses a pairing of both methods in hopes of a more accurate assignment of annual growth increments in shell carbonate and thus a more accurate growth rate and age determination (Krantz et al., 1984; Romanek et al., 1987; Jones, 1988).

Years of growth and age are determined by counting the number of  $\delta^{18}$ O cycles in an isotopic record (Erlenkeuser and Wefer, 1981; Jones et al., 1986). Starting with the collection date of live molluscs, the  $\delta^{18}$ O values from an isotopic record can be validated by a comparison to the theoretical  $\delta^{18}$ O values, based upon the  $\delta^{18}$ O and temperature of water (Krantz et al., 1984; Romanek and Grossman, 1989; Krantz et al., 1987; Jones et al., 1989). To determine the growth rate using stable isotopes, a graph is constructed using the shell height vs. the number of seasonal cycles in the isotopic record (Erlenkeuser and Wefer, 1981; Krantz et al., 1984; Romanek et al., 1987; Jones et al., 1989).

Growth rates calculated through the use of isotopic records have yielded information on shell deposition. The isotopic records support the observation that, in general, molluscs decrease the rate of shell growth as they mature, as measured by shell height (Killingley and Berger, 1979; Erlenkeuser and Wefer, 1981; Jones, 1981). Additionally, increases in molluscan growth rate can occur in either a warm season (Erlenkeuser and Wefer, 1981) or a cool season (Killingley and Berger, 1979; Jones, 1980a), suggesting that growth is influenced by temperature and/or the availability of food, nutrients, or oxygen (Jones, 1981).

#### Fossils, Archaeology, and Stable Isotopes

Stable isotope analysis expanded beyond the study of modern molluscs when researchers began to demonstrate that fossil and archaeological molluscs could be used to measure paleotemperatures (Epstein and Lowenstam, 1953; Keith et al., 1964; Emiliani et al., 1964; Rhoads and Lutz, 1980). Continuing research on fossil molluscs demonstrated that paleoclimates have either fluctuated in the past (Krantz et al., 1987) or showed no difference from modern climate (Killingley and Berger, 1979; Donner and Nord, 1986). Similar paleoclimate research on archaeological molluscs using isotopic analysis is helpful to the field of archaeology in many ways. Rollins et al. (1987) concluded that major climatic events, such as El Niño, could be recognized by stable isotopic analysis of shells from archaeological sites. Shackleton and Renfrew (1970) clarified economic questions, namely trade, using oxygen isotopic analysis of molluscs. Most significant was the determination of a season of capture, from which inferences could be made about the season of occupation on archaeological sites (Shackleton, 1973; Clark, 1979; Killingley and Berger, 1979; Killingley, 1981; Deith, 1983; 1986; Quitmyer, Jones, and Arnold, 1997).

## CHAPTER 3 METHODOLOGY

#### **Field Location**

San Salvador (24°07'N, 74°52'W), one of the eastern most islands of the Bahamas archipelago (Figure 3.1), is located on an isolated carbonate platform. About 20 km long and 11 km wide, San Salvador has a topography that is dominated by eolianite ridges and karstic features (Carew and Mylroie, 1997). The surficial geology on San Salvador is composed of Pleistocene and Holocene carbonate rocks (Titus, 1986; Carew and Mylroie, 1997). The depositional history of San Salvador was controlled by glacioeustatic sea-level changes (Carew and Mylroie, 1997). San Salvador Island intercepts the Antilles current, which flows northwestwardly at 0.6 knots (Hydrographic Chart, 1988). San Salvador experiences a tropical climate with short periods of heavy rain occurring throughout the year. More than 75% of the precipitation is evapotranspired and runoff is limited due to the karst topography (Tarbox, 1986). Surface bodies of freshwater are nonexistent, and hypersaline lakes dominate the landscape (Landsat Image 1985; Carew and Mylroie, 1997). There is very little groundwater and the freshwater lenses that do exist are discontinuous, and located mainly under higher points of elevation (Kunze and Weir, 1986).

Pigeon Creek ('Creek' is the British term for lagoon), located on the windward side of the island, has a northern and southern branch that converge at a tidal inlet (see Figure 3.1; Boardman and Carney, 1996). The salinity of Pigeon Creek varies geographically from normal marine conditions of 36-37‰ near the tidal inlet to as high as 50‰ at the uppermost part of northern Pigeon Creek (Teeter, 1985; Mitchell, 1986). Tidal fluctuations can cause the level of the lagoon to drop 40 to 80 cm (Boardman and Carney, 1996). A tidal channel, 1 to 3 meters deep, exists in the center of both arms of



**Figure 3.1.** San Salvador Island, showing location of Pigeon Creek and the Pigeon Creek archaeological site. Inset of the Bahama Islands, showing the locations of San Salvador, Grand Bahama, and Lee Stocking (modified from Craton and Saunders, 1992).

the lagoon and converges at the inlet, where outgoing currents (ebb) attain speeds of >70 cm/s (1.5 knots; Teeter, 1985; Boardman and Carney, 1996). The ebb tide is responsible for coarse sediment transport, including *Codakia* shells (Boardman and Carney, 1996). *Thalassia* meadows parallel this tidal channel with mangroves lining the banks of the lagoon. Scour pits in the tidal channel form when currents erode the shallow slopes of the channel to form steep sides that can be as deep as 5 m (Boardman and Carney, 1996). Within these steep sides, dead, articulated shells of *Codakia* are found embedded amongst the thick rhizomes of *Thalassia* in life position.

The Pigeon Creek archaeological site is located on the leeward slope of an eolianite ridge (Figure 3.1), which probably provided the indigenous people, the Lucayans, with some protection from ocean storms and enemy attacks (Rose, 1982). The location also provided the Lucayans with ready access to the marine resources of the ocean and the lagoon (Figures 3.1 and 3.2; Rose, 1982). The shape of Pigeon Creek lagoon has changed little since the occupation of the archaeological site (Mitchell and Keegan, 1987). The Pigeon Creek settlement, one of several archaeological sites that border the lagoon, may be the largest site on San Salvador (Rose, 1982; Mitchell and Keegan, 1987). There are several middens, or prehistoric landfills, found within the stratigraphy of the Pigeon Creek archaeological site and range in age from about AD 1000 to AD1600 (Rose, 1982; Berman and Hutcheson, 2000). The uppermost midden was radiocarbon dated site ( $380 \pm 40^{-14}$ C BP; Beta 132345 cal AD 1440-1530) using a piece of charred wood collected in 1997 at a depth of 20-30 centimeters from square S 104 E 20.

#### **Specimen Collection**

#### Modern Clams

All specimens of *Codakia* were collected over the period of a week in May 1999 and June 2000 from the southern arm of Pigeon Creek lagoon (Figure 3.3). This



**Figure 3.2. A.** Photograph of the Pigeon Creek archaeological excavations viewed from the trail that leads up to the site. **B.** Photograph of Pigeon Creek viewed from the archaeological site at the top of the hill.



**Figure 3.2.** Pigeon Creek showing the collection area for modern *Codakia orbicularis*. Live specimens were collected near the boat dock and the shells were collected in the area marked by the purple box (modified from Robinson and Davis, 1999).

collection site was chosen because the area had easy access from the road via a boat dock to *Thalassia* beds where *Codakia* live. Additionally, *Codakia* was collected from near the tidal inlet for two reasons: 1) *Codakia* were known to live in this area, and 2) the salinity of the water was near that to open ocean water. Five live specimens of *Codakia orbicularis* were collected from within *Thalassia* beds located on tidal flats in the Pigeon Creek lagoon (Figure 3.4) . *Codakia* were collected by hand from approximately 20-30 cm below the sediment-water interface at low tide, when the water level was approximately one meter. The specimens were sacrificed soon after collection by boiling or leaving them out of the water until the shells opened at which time the tissue was removed with a knife.

Articulated valves of *Codakia orbicularis* were collected in addition to the live clams. Articulated valves were collected for two reasons: 1) *Codakia* are easily overfished (Berg and Alatalo, 1982) and the Bahamian government carefully monitors the collection of them, and 2) the live specimens collected were relatively small in size based upon previous estimates of growth (Berg and Alatalo, 1984), and larger specimens were also needed for this study. Articulated valves in good condition were specifically collected; taphonomically, the organic ligament that binds the valves decays relatively quickly upon death, so articulated shells presumably came from clams that recently died. Numerous articulated shells of *Codakia* were collected from the bottom of the tidal channel near the collection site of the live specimens (Figure 3.5). All specimens were immediately labeled and bagged for transport back to the laboratory.

#### Archaeological Codakia

A large number of archaeological *Codakia orbicularis* specimens were found in a midden (radiocarbon age  $380 \pm 40$  BP) on the Pigeon Creek archaeological site. Numerous shells of *Codakia orbicularis* were excavated and donated by Dr. Mary Jane Berman and Dr. Perry L. Gnivecki of Miami University (Ohio) from two squares



**Figure 3.4.** Photograph of the area of Pigeon Creek where live specimens of *Codakia orbicularis* were collected.


**Figure 3.5.** Underwater photograph showing a shell deposit, including *Codakia orbicularis*, at the bottom of the tidal channel in Pigeon Creek.

(S 101, E 27 & S 102, E 25) that lie adjacent to the radiocarbon dated square (S 104, E 20). There is a marked increase in the number of *Codakia* shells in this midden relative to the number found in an earlier-dated midden within the Pigeon Creek archaeological sites. A low number of *Codakia* shells in these earlier middens might be attributed to the greater abundance of vegetation and terrestrial animals on the islands. A greater abundance of vegetation and animals on the Bahama Islands might have allowed the initial settlers, the Lucayans, to initially ignore shellfish, and in particular the infaunal molluscs, as a food source (Keegan, 1989). These infaunal molluscs, namely *Codakia* orbicularis, might have been collected after the easier-to-collect food resources had been exhausted or the human population exceeded the available resources (Keegan, 1989).

## Water Samples for Isotopic Analysis

Water samples were taken for isotopic analysis at the sites where the live specimens and the articulated shells of *Codakia* were collected. Water samples were also collected at French Bay (see Figure 3.1), an open ocean environment, for comparison with waters from the more restricted environment of Pigeon Creek. To prevent isotopic fractionation, water samples were collected and sealed under water. Salinity and sea surface temperature measurements were taken with a YSI Model 33 salinity meter at the water sampling sites.

The lack of a robust seasonal water temperature data set from Pigeon Creek lagoon prompted the use of additional sea surface temperature records from Lee Stocking Island (23°46'N, 76°07'W; Perry, 2001) and the Central Bahamas (Bahamas Dept. of Met., 2000). The sea surface temperatures from Lee Stocking Island, over an approximate eleven year period, were taken from three locations: 1) seagrass bed and tidal channel (3m depth), 2) patch reef (4m depth), and 3) coral reef (16m depth) (Perry, 2001).

#### Laboratory Methods

#### Sample Preparation

Modern and archaeological *Codakia* specimens were tested for mineralogical composition using a SCINTAG XDS–2000 diffractometer. Sample preparation involved sectioning off a portion of the shell from the umbo to the lip with a diamond wafer blade saw (ISOMET) and then powdering the section with a mortar and pestle. This method was repeated for both the modern and archaeological specimens. If shell aragonite was altered, it was then assumed that the isotopic composition would also be altered.

Cleaning procedures were performed to avoid the sampling of contamination, such as encrusting organisms and organic debris, on the external shell surface. Shells were soaked for ten minutes in a 5.25% sodium hypochlorite reagent solution. The bleaching process itself has no effect on the isotopic composition of the shell (Grossman and Ku, 1986). Immediately following the bleaching process, the shell was scrubbed with a wire brush, rinsed well with deionized water, and then air dried for 24 hours.

#### Sampling Technique

Four modern and four archaeological specimens of *Codakia orbicularis* were chosen for isotopic analysis. The two largest shells from live specimens, the two largest articulated (recently dead) shells, and four archaeological specimens in good condition were chosen. The shells were sampled incrementally from the umbo to the shell margin. Using a dental drill, a series of point samples were drilled on the outer surface parallel to growth increments until approximately 3-4 mg of powdered aragonite was collected for isotopic analysis. Replicates (about 10% of total samples) were collected by recounting increments on the shell to a previously drilled increment and then drilling in a new area of that increment. Material was drilled only in the outer layer of shell to

avoid contamination with carbonate that may have been deposited at a different time interval (Keith et al., 1964). The distance from the umbo to each drilled increment was then measured with calipers.

Material was sampled from the initial specimen, which was captured alive (PCL-UN2), starting at ~16mm of shell height, at a resolution that would achieve an ontogenetic sequence of isotope values within which annual cycles could then determined. Sampling was started at ~16 mm because the growth increments approximated the width of the drill bit (0.4mm) at this shell height. The results showed that many samples were analyzed within a single annual cycle. This result, in combination with the Berg and Alatalo (1984) growth curve, led to the development of a revised sampling strategy. The seven remaining specimens were sampled, starting at 25-30mm, at a lower resolution that still permitted the determination of annual cycles based upon the isotope records. However, this new sampling strategy may or may not lead to bias when the resulting  $\delta^{18}$ O values are analyzed statistically.

## Isotope Analysis

Drilled carbonate samples were transferred with a microspatula to vessels for analysis on a continuous flow isotope ratio mass spectrometer with a Gas Bench peripheral device. Carbon dioxide gas was extracted from aragonite by purging the vessels with He and reacting the samples with 100% phosphoric acid at ~25°C. The stable isotope ratios were measured using a Finnigan Delta +XL isotope ratio mass spectrometer and calibrated to V-PDB using the working standard NBS-19 ( $\delta^{18}O =$ -2.20‰ and  $\delta^{13}C =$  +1.95‰; Hoefs, 1997). One NBS-19 sample was run after approximately every eight samples. Precision for standard analyses was ±0.1‰ (1 $\sigma$ ) for oxygen and ±0.1‰ (1 $\sigma$ ) for carbon based upon repeated analyses of NBS-19. The averages, standard deviations, maximum and minimum values for the differences between original data and replicates are listed in Table 3.1. All replicate data,

**Table 3.1** The difference between original data and replicates for *Codakia* samples. The average, standard deviation, maximum, and minimum (absolute) values for the differences in replicates are listed here. The complete list of replicate data is reported in Appendix A.

		δ13C	$\delta^{_{18}}\mathbf{O}$
	Mean	0.19	0.47
PCL-UN2	Standard Dev.	0.07	0.04
1 CL-0112	Maximum	0.24	0.50
	Minimum	0.14	0.45
	Mean	0.34	0.33
DCI DO2	Standard Dev.	0.41	0.25
PCL-DU2	Maximum	1.12	0.79
	Minimum	0.01	0.00
	Mean	0.28	0.40
DCM UN21	Standard Dev.	0.19	0.28
	Maximum	0.61	0.90
	Minimum	0.02	0.00
	Mean	0.33	0.85
DCM UN22	Standard Dev.	0.30	0.35
I CIVI-UIN22	Maximum	0.88	1.57
	Minimum	0.00	0.33
	Mean	0.66	0.74
	Standard Dev.	0.50	0.50
I CA-0	Maximum	1.14	1.23
	Minimum	0.14	0.24
	Mean	0.53	0.29
ΡΟΛ-9	Standard Dev.	0.22	0.18
I CA-J	Maximum	0.67	0.57
	Minimum	0.15	0.11
	Mean	0.54	0.84
	Standard Dev.	0.45	0.57
FCA-10	Maximum	1.56	1.53
	Minimum	0.12	0.02

descriptive statistics, and daily calculations of standard precision are listed in Appendix A. Replicates are not used in the interpretation of the isotope data but are presented here as an estimate of precision for samples of *Codakia* aragonite.

From the water collection bottles, 1.2 mL of water was transferred with a clean, dry syringe to a vial that were previously purged and filled with pure CO<sub>2</sub>. The seawater was equilibrated with the pure CO<sub>2</sub> by shaking in a 25°C bath for approximately three hours. The oxygen isotope ratios were measured using a Finnigan MAT Delta E isotope ratio mass spectrometer and calibrated with a laboratory standard (Athens Tap Water,  $\delta^{18}O = -4.80\%$ ) to V-SMOW. Precision for  $\delta^{18}O$  was  $\pm 0.1\%$ (1 $\sigma$ ).

## **Data Analysis**

Paleotemperatures were calculated using the equation from Grossman and Ku (1986) for biogenic aragonite:

$$T^{\circ}C = 21.8 - 4.69(\delta^{18}O_{ar} - \delta_{w})$$

where  $\delta^{18}O_{ar}$  is the  $\delta^{18}O$  value of aragonite and  $\delta_w$  is the average isotopic composition of Pigeon Creek water minus 0.2‰, a correction factor determined by Epstein et al. (1953) to correct the  $\delta^{18}O$  of CO<sub>2</sub> equilibrated with mean ocean water at 25°C on the SMOW scale to equal that of CO<sub>2</sub> derived from PDB by phosphoric acid digestion at 25°C.

All statistical analyses were performed using MSEXCEL98 to test question #6 posed in the Introduction. A group of all modern isotope values were compared to a group of all archaeological isotope values. All data were tested for normality using the Kolmogorov-Smirnov test as described in Sokal and Rohlf (1981). The result of a F-test determined that a two-tailed student *t*-test for unequal variance should be used to test the research question #6 (from the Introduction). The null hypothesis was:

 $H_0$ : There is no difference in means of the  $\delta^{18}$ O values between the modern and the archaeological clams.

# CHAPTER 4 RESULTS

# Water

Water samples were collected from the shore of Pigeon Creek lagoon on three dry days and one rainy day in May 1999, one dry day in January 2000, and one dry day in June 2000. One sample was also collected from 3 meters offshore in May 1999. Water samples were also collected at French Bay on one dry and one rainy day in May 1999 to represent the open ocean.

Summer sea surface temperatures from Pigeon Creek were fairly consistent, averaging  $28.4 \pm 0.8$ °C (1 $\sigma$ ), not including a temperature measurement after a rainstorm in May 1999 (26.9°C; Table 4.1). The  $\delta^{18}$ O values for south Pigeon Creek in May 1999 and June 2000 ranged from 0.96‰ to 1.36‰ and averaged  $1.2 \pm 0.1\%$  (1 $\sigma$ ). The  $\delta^{13}$ C values for the same months ranged from 0.83‰ to 0.97‰ and averaged  $0.9 \pm 0.1\%$  (1 $\sigma$ ). Sea surface temperature and  $\delta^{18}$ O for south Pigeon Creek in January 2000 were 21.5°C and 0.75‰ respectively. The samples from French Bay averaged 27.5 ± 1.4°C (1 $\sigma$ ) in sea surface temperature,  $0.9 \pm 0.1\%$  (1 $\sigma$ ) in  $\delta^{18}$ O of water, and  $0.8 \pm 0.1\%$  (1 $\sigma$ ) in  $\delta^{13}$ C of water. Summer sea surface temperatures for French Bay were similar to Pigeon Creek, while the  $\delta^{18}$ O values were slightly lower.

Historical temperature measurements from Lee Stocking Island and Central Bahamas were averaged by month creating a 10-year monthly data set of maximum and minimum temperatures for the seagrass, patch reef, and coral reef localities (Figure 4.1). The Pigeon Creek sea surface temperatures measured in this study were also plotted on the graph, creating an "envelope" of sea surface temperatures from which monthly maximum and minimum sea surface temperatures were defined (Table 4.2). The Pigeon Creek data fall within the "envelope" of sea surface temperatures defined by the Lee

**Table 4.1.** Sea surface temperature,  $\delta^{18}$ O, and  $\delta^{13}$ C of water samples from San Salvador Island. Summer averages for south Pigeon Creek were computed using the values for the May-99 samples and the June-00 sample. Annual averages and weighted averages for south Pigeon Creek were computed using the values for May-99, June-00, and Jan-00.

Location and Date		$\delta^{\scriptscriptstyle 18}O_{\text{ H20(SMOW)}}$	δ <sup>13</sup> C	SST C
North Pigeon Creek	5/24/99	2.07	0.81	29.9
	After rain5/25/99	1.19	0.97	26.9
	3m out5/26/99	1.14	0.83	28.5
South Digoon	5/26/99	1.26	0.93	28.5
Creek	5/27/99	0.96	0.84	29.0
CIEEK	5/28/99	1.11	0.87	29.0
	1/27/00	0.75	1.01	21.5
	6/7/00	1.36	0.88	28.5
French Bay	After rain5/25/99	0.81	0.88	26.5
Thenen Day	5/26/99	0.92	0.75	28.5
	Summer averages of South Pigeon Creek	$1.2 \pm 0.1$	$0.9 \pm 0.1$	28.4±0.8
$\left( \begin{array}{c} \overline{\mathbf{x}}_{all} \\ \hline 2 \end{array} \right)$	Annual Averages of South Pigeon Creek	$1.1 \pm 0.2$	0.9 ± 0.1	27.4±2.7
(-				
$\begin{bmatrix} x_{summer} + x_{winter} \\ \hline 2 \end{bmatrix}$	Weighted Averages of South Pigeon Creek	1.0±0.3	0.9 ± 0.1	25.0±4.9



**Figure 4.1.** "Envelope" of maximum and minimum sea surface temperatures. LSI = Lee Stocking Island.

	Min	Max
January	18.9	27.0
February	18.9	28.3
March	20.1	29.1
April	22.3	29.9
May	22.5	31.3
June	24.3	33.0
July	23.5	33.4
August	27.1	33.1
September	26.2	32.0
October	24.9	31.7
November	23.6	29.9
December	20.8	28.3

**Table 4.2.** Monthly maximum and minimum sea surface temperatures (°C) determined from the monthly range of observed temperatures and historical records.

Stocking Island data (see Figure 4.1).

#### Carbonate

The mineralogy of five modern and two archaeological *Codakia* shells were verified to be aragonite by XRD analysis, which indicates the shell material is unaltered in both modern and archaeological specimens. Eight specimens, different shells from those analyzed on the XRD, yielded a total of 354 powdered carbonate samples, all collected from the outer surface of the shell. The resulting  $\delta^{18}$ O and  $\delta^{13}$ C values are summarized in Table 4.3 and plotted against shell height for each specimen in Figures 4.2 to 4.9.

For purposes of this study, a cycle is defined by relative "most negative"  $\delta^{18}$ O values in the isotope profiles. The summer season was arbitrarily picked as the starting and ending point of an oxygen isotope cycle. Based on these criteria, one complete cycle was identified in the record of a live specimen (PCL-UN2) and approximately two cycles were identified in the record of another live specimen (PCL-BO2) (see Figure 4.2 A. and 4.5 A.). Additionally, about five cycles were identified in two records of articulated-dead specimens (PCM-UN21 and PCM-UN22) (see Figures 4.4 A. and 4.5 A.). Finally, the number of cycles found in the isotope records of the archaeological specimens was five for PCA-6 and PCA-7 and four for PCA-9 and PCA-10. While the modern isotope values cycle with similar amplitudes and periods, a difference is visually observed between the modern cycles and those of the archaeological specimens. Furthermore, the cycles within the  $\delta^{18}$ O record for an archaeological specimen (PCA-10) are different from all of the other  $\delta^{18}$ O records.

"Dark increments" were identified on the shell surface of all *Codakia* specimens and marked on Figures 4.2 A.-4.9 A.. The "dark increments" were defined as exhibiting darker, translucent carbonate material that was prominently recessed into the shell relative to other increments. However, if an increment possessed only the dark, translucent material or it only exhibited a more prominent cut into the shell, then the increment was

of drilled samples, and the average, maximum, and	
he height of shell, the number	ope values for each specimer
Table 4.3. The	minimum isotc

				Number of	Carl	9% UOC	0	Oxy	gen %	0
		Specimens	Height	Drilled Samples	Average ±0.1	Max	Min	Average ±0.1	Max	Min
	I iva Charimane	PCL-UN2	39.49	49	0.1	1.3	-0.5	-0.3	0.8	-0.9
Madam	ensinode att	PCL-BO2	57.12	29	1.0	1.9	0.2	-0.6	0.5	-1.5
	Articulated Shalls	PCM-UN21	79.88	40	2.3	3.4	0.1	-0.1	0.7	-1.0
		PCM-UN22	81.37	55	2.8	4.0	0.8	0.04	0.8	-0.7
		PCA-6	74.61	55	2.6	3.6	1.4	0.4	1.1	-0.6
A nobocodora	U U V U V U V U V V V V V V V V V V V V	PCA-7	72.90	47	2.0	3.0	-1.6	0.1	1.0	-1.2
	(.U.A. U.T.)	PCA-9	66.76	40	1.9	3.0	-0.01	-0.2	1.2	-1.6
		PCA-10	59.40	39	1.5	3.0	-1.1	0.5	1.9	-1.3



**Figure 4.2.** PCL-UN2: A.  $\delta^{18}$ O values. Numbers represent approximate ages. Red squares identify "dark" increments and pink squares identify "disturbance" increments. Green diamonds are replicates values. B.  $\delta^{13}$ C values. Boxes outline juvenile and adult growth phases.



**Figure 4.3.** PCL-BO2: A.  $\delta^{18}$ O values. Numbers represent approximate ages. Red squares identify "dark" increments and pink squares identify "disturbance" increments. Green diamonds are replicates values. B.  $\delta^{13}$ C values. Boxes outline juvenile and adult growth phases.



**Figure 4.4.** PCM-UN21: A.  $\delta^{18}$ O values. Brackets identify cycles. Numbers represent approximate ages. Red squares identify "dark" increments and pink squares identify "disturbance" increments. Green diamonds are replicates values. B.  $\delta^{13}$ C values. Boxes outline juvenile and adult growth phases.



**Figure 4.5.** PCM-UN22: A.  $\delta^{18}$ O values. Brackets identify cycles. Numbers represent approximate ages. Red squares identify "dark" increments and pink squares identify "disturbance" increments. Green diamonds are replicates values. B.  $\delta^{13}$ C values. Boxes outline juvenile and adult growth phases.



**Figure 4.6.** PCA-6: A.  $\delta^{18}$ O values. Brackets identify cycles. Numbers represent approximate ages. Red squares identify "dark" increments and pink squares identify "disturbance" increments. Green diamonds are replicates values. B.  $\delta^{13}$ C values. Box outlines possible adult growth phase.



**Figure 4.7.** PCA-7: A.  $\delta^{18}$ O values. Brackets identify cycles. Numbers represent approximate ages. Red squares identify "dark" increments and pink squares identify "disturbance" increments. B.  $\delta^{13}$ C values. Boxes outline juvenile and adult growth phases.



**Figure 4.8.** PCA-9: A.  $\delta^{18}$ O values. Brackets identify cycles. Numbers represent approximate ages. Red squares identify "dark" increments and pink squares identify "disturbance" increments. Green diamonds are replicates values. B.  $\delta^{13}$ C values. Boxes outline juvenile and adult growth phases.



**Figure 4.9.** PCA-10: A.  $\delta^{18}$ O values. Brackets identify cycles. Numbers represent approximate ages. Red squares identify "dark" increments and pink squares identify "disturbance" increments. Green diamonds are replicates values. B.  $\delta^{13}$ C values. Boxes outline juvenile and adult growth phases.

identified as a "disturbance increment" (see Figures 4.2 A.-4.9 A.). All the isotope values for each specimen are listed in Appendix B.

# **Statistics**

The K-S test for normality indicated that the data were normally distributed (Table 4.4). The F-test of modern versus archaeological groups indicated an unequal variance (F>Crit. F; Table 4.5 A.). As a result of the outcome of the F-test, the modern and archaeological groups were analyzed using a *t*-test for unequal variance, which rejected the null hypothesis (p<0.025; Table 4.5 B.). The null hypothesis was that there is no difference in means of the  $\delta^{18}$ O values between the modern and the archaeological clams. Complete statistical tests are listed in Appendix C.

**Table 4.4.** Results of the K-S test: D-values were less then the Critical D, thus the data were normally distributed.

	PCL-UN2	PCL-BO2	PCM-UN21	PCM-UN22
D	0.15	0.16	0.13	0.13
Critical D	0.20	0.25	0.21	0.21

	PCA-6	PCA-7	PCA-9	PCA-10
D	0.10	0.11	0.11	0.08
Critical D	0.20	0.20	0.21	0.21

D<Crit.D-accept H<sub>o</sub>

**Table 4.5.** Isotope data were compiled into two groups: the modern and the archaeological. F-test of modern vs. archaeological group (Table 4.5. A). *T*-test for unequal variance of the modern vs. archaeological groups of data (Table 4.5. B).

A. F-test

F-statistic	1.36
Critical F-statistic	1.29
	reject H <sub>0</sub>

reject  $H_0$  = variances are not equal

## B. T-test

p-value - two-tail	0.0000000001
	reject H <sub>0</sub>

 $p < 0.025 \label{eq:p}$  reject  $H_{\scriptscriptstyle 0} {=}$  significant difference in the means

# CHAPTER 5 DISCUSSION

# Modeling

The comparison of predicted  $\delta^{18}$ O values to observed  $\delta^{18}$ O values determines whether a mollusc precipitates its shell in equilibrium with the surrounding seawater (Krantz et al., 1984; Jones et al., 1986; Krantz et al., 1987; Romanek et al., 1987; Bemis and Geary, 1996). Predicted  $\delta^{18}$ O values may be calculated for an aragonitic mollusc shell from the oxygen isotopic composition of the ambient seawater and its water temperature using the aragonite paleotemperature equation of Grossman and Ku (1986) rearranged to solve for  $\delta^{18}O_{ar}$ :

$$\delta^{18}O_{ar} = ((T^{\circ}C-21.8)/-4.69) + \delta_{w}$$

where T°C is the interpolated sea surface temperature (from Table 4.2) and  $\delta_w$  is the average isotopic composition of water minus 0.2‰. Inputting monthly maximum and minimum sea surface temperatures from Table 4.2 and the average  $\delta^{18}$ O of winter and summer Pigeon Creek water (Table 4.1) into the paleotemperature equation permitted the calculation of  $\delta^{18}$ O compositions for aragonite deposited in equilibrium with waters collected from southern Pigeon Creek (black lines; Figure 5.1). Uncertainty in sea surface temperatures could affect the calculated range of  $\delta^{18}$ O for aragonite in the model, although the range in values noted for the Bahamian region (Table 4.2) is significantly greater than that observed at Pigeon Creek (Table 4.1).

The  $\delta^{18}$ O values from all four modern specimens fit within the boundaries of the south Pigeon Creek model suggesting that *Codakia* precipitates its shell in equilibrium with the surrounding seawater (Figure 5.2). However, upon closer examination the most positive  $\delta^{18}$ O values from the modern specimens do not correspond with the most positive  $\delta^{18}$ O values for the model. The most positive  $\delta^{18}$ O values from the modern



**Figure 5.1.** Seasonal  $\delta^{18}O_{ar}$  equilibrium model for southern Pigeon Creek calculated from the Grossman and Ku (1986) paleotemperature equation, using the observed seasonal range in temperature for the Bahamian region (Table 4.2) and the average of winter and summer  $\delta^{18}O$  values for south Pigeon Creek water (Table 4.1; black lines). A second model for south Pigeon Creek (red lines) was calculated using the observed seasonal range in temperature for the Bahamian region (Table 4.2) and the average of the sum of summer  $\delta^{18}O$  values and the one winter  $\delta^{18}O$  value for south Pigeon Creek water (Table 4.1). A third model for south Pigeon Creek (blue lines) was calculated using the observed seasonal range in temperature for the Bahamian region (Table 4.2) and the average of summer  $\delta^{18}O_w$  values and the winter  $\delta^{18}O_w$  value (Table 4.1).



**Figure 5.2.** A plot of all the modern  $\delta^{18}$ O values (dark blue circles) compared to the predicted range of values in the south Pigeon Creek model (black lines). The second south Pigeon Creek model that used a weighted average of  $\delta^{18}$ O of the ambient seawater is plotted for comparison (red lines). The third south Pigeon Creek model that utilized both the summer and winter  $\delta^{18}O_{H2O}$  values is again plotted for comparison (blues lines). A north Pigeon Creek model is also plotted on the figure for comparison (green lines), which used the  $\delta^{18}O_{H2O}$  for values measured at this locality (see Table 4.1).

specimens average about 0.8‰, while the model values are as high as about 1.5‰, which might have resulted from growth cessations that occurred during extreme winter temperatures. A more plausible possibility is that the weighting of the average of  $\delta^{18}O_{H20}$  favored the summer values (n=6) to the winter value (n=1; see Table 4.1). The south Pigeon Creek model (black lines on Figure 5.1) was modified using a different oxygen isotope composition of the ambient seawater, which was the sum of mean summer  $\delta^{18}O_{H2O}$  values and one winter  $\delta^{18}O_{H2O}$  value and then dividing that sum by two (see Table 4.1; red lines on Figures 5.1, 5.2). The  $\delta^{18}$ O values from all four modern specimens fit within the boundaries of the south Pigeon Creek model that was calculated with the weighted average of  $\delta^{18}O_{H20}$ . While this model seems to be a better fit of the modern  $\delta^{18}O_{ar}$  values, the most positive winter values still do not correspond well with the most positive  $\delta^{18}$ O values of the model. Perhaps the difference in the most positive values between the model and the actual  $\delta^{18}O_{ar}$  values is due to homogenization of carbonate samples during drilling. A more fine-scaled resolution of incremental sampling is needed to determine whether this might be the reason for the difference in maximum  $\delta^{18}$ O values.

The difference between the most positive observed  $\delta^{18}O_{ar}$  values and model  $\delta^{18}O_{ar}$  values might also be attributed to an inaccurate representation of the actual winter sea surface temperatures at Pigeon Creek (Table 4.1) by the proxied winter sea surface temperatures for the Bahamas (Table 4.2). This possibility cannot be tested since only one water sample was collected from Pigeon Creek in the winter season. However, if this single data point, collected from Pigeon Creek (Table 4.1), is an accurate representation of the actual value, then this indicates that the  $\delta^{18}O$  of water changes seasonally. This fluctuation in  $\delta^{18}O_{H2O}$  has been demonstrated in the tropical waters of the Pacific Ocean (Swart et al., 1983). Thus, another model for south Pigeon Creek was created by lowering the winter  $\delta_w$  of the model (black lines on Figure 5.1) to the  $\delta^{18}O_{H2O}$  value recorded at Pigeon Creek (Table 4.1; blue lines on Figures 5.1, 5.2). The upper

winter values were shifted in a negative direction relative to the two previous south Pigeon Creek models and are much closer to the observed  $\delta^{18}O_{ar}$  (see Figure 5.2).

If the  $\delta^{18}O_{H20}$  for the winter Pigeon Creek (Table 4.1) is an accurate representation of the actual value, then so might the recorded sea surface temperature for winter Pigeon Creek. By increasing the winter sea surface temperatures (Table 4.2) to equal 21.5 °C, which is the value recorded in January for Pigeon Creek (Table 4.1), then the resulting winter  $\delta^{18}O_{ar}$  decreased for each model in Figure 5.1. The maximum values of these resulting winter  $\delta^{18}O_{ar}$  were ~0.98‰ for the first south Pigeon Creek model (black lines; Figures 5.1, 5.2), ~0.81‰ for the second model (red lines), and ~0.59‰ for the third model (blue lines). These results suggest that the actual monthly minimum sea surface temperatures for Pigeon Creek might be higher than those proxied from Lee Stocking Island (Table 4.2). The most probable model for modern south Pigeon Creek incorporates a combination of a seasonal  $\delta^{18}O_{H20}$  shift and higher annual minimum sea surface temperatures. However, more winter water samples collected from Pigeon Creek are needed to determine which model is the most accurate representation of the actual  $\delta^{18}O$  values of aragonite precipitated in ambient seawater.

A model representing a high saline and evaporative environment was created using the  $\delta^{18}O_{H20}$  of northern Pigeon Creek (Table 4.1; Figure 5.3) and the monthly maximum and minimum sea surface temperatures from Table 4.2. Aragonite from molluscs that lived in an environment such as north Pigeon Creek would yield a more positive range of  $\delta^{18}O$  values relative to the range of  $\delta^{18}O$  values for south Pigeon Creek as shown in Figure 5.3. The modern  $\delta^{18}O$  values do not fit within the range of the model for north Pigeon Creek (see Figure 5.3).

Alternatively, dilution of seawater with rain would reduce the  $\delta^{18}$ O of the seawater and would subsequently cause  $\delta^{18}$ O of carbonate precipitated to be more negative than it would otherwise. However, for the field days when it rained, no



**Figure 5.3.** Seasonal  $\delta^{18}$ O equilibrium models for north Pigeon Creek (green line) and south Pigeon Creek (colors identified on Figure 5.1) calculated from the Grossman and Ku (1986) paleotemperature equation. The model for north Pigeon Creek shifted in a positive direction relative to the models for south Pigeon Creek.

dilution of seawater could be detected by changes in either salinity or  $\delta^{18}$ O. Additionally, other sources of freshwater, i.e. streams, are currently not present at Pigeon Creek lagoon. The dilution of seawater remains a concern for clams of unknown provenance, e.g. archaeological specimens, if climatic conditions were considerably different than today, i.e. heavier rains of longer duration. This would probably impact the environment in other ways that would be noticeable (faunal/flora changes) and this has not been observed. If, however, several data points had fallen inexplicably outside the lower range of the Pigeon Creek models, an argument could have been made that these data points might have been affected by freshwater, but all  $\delta^{18}$ O values fit within the lower boundary of the models.

The archaeological  $\delta^{18}O_{ar}$  values do not fit within the boundaries of any one south Pigeon Creek model, and the range of archaeological  $\delta^{18}O$  values exceeds the range of the modern  $\delta^{18}O$  values (Figures 5.2, 5.4; Table 4.3). More specifically, a number of archaeological  $\delta^{18}O$  values are more positive than those observed in the modern. The temperature and  $\delta^{18}O$  of seawater during archaeological times is unknown, so the effects of a variety of  $\delta^{18}O_{H2O}$  values and water temperatures on the models in Figure 5.1 were investigated in an attempt to fit the range of  $\delta^{18}O_{ar}$  of the archaeological *Codakia* within a model.

By altering the variables in the Grossman and Ku (1986) paleotemperature equation, three hypothetical models (A-C) were created to fit the observed archaeological  $\delta^{18}O_{ar}$  (Figure 5.5). Two of the hypothetical models (A and B) assumed that the  $\delta^{18}O_{w}$  remained constant throughout the year in both the modern and archaeological time periods. By using the annual average  $\delta^{18}O_{w}$  for winter and summer Pigeon Creek (Table 4.1), the minimum winter temperatures (Nov-Mar) have to be decreased by 1.65°C to fit the range of the archaeological data (Model A; Figure 5.5). Using the weighted average of  $\delta^{18}O_{w}$  for winter and summer Pigeon Creek (Table 4.1), the annual monthly minimum temperatures have to be reduced by 2.33°C to fit the



**Figure 5.4.** A plot of all the archaeological  $\delta^{18}$ O values to see if the data falls within the range of the south Pigeon Creek models (black, red, and blue lines). The north Pigeon Creek model is also plotted on the figure for comparison (green lines). The  $\delta^{18}$ O range of archaeological data not occupied by the modern data is bracketed. All of the archaeological  $\delta^{18}$ O values do not fit within the range of the model for north Pigeon Creek.



**Figure 5.5.** The three  $\delta^{18}$ O models for modern-day south Pigeon Creek compared to the models created to fit the range of archaeological data (Table 4.3). Model A (purple open squares) was created using the annual average of  $\delta^{18}O_{H2O}$  for Pigeon Creek (Table 4.1) and the minimum winter temperatures had to be decreased by 1.65°C to fit the range of the archaeological data. Model B (turquoise circles) was created using the weighted average of  $\delta^{18}O_{H2O}$  for Pigeon Creek (Table 4.1) and the minimum monthly temperatures had to be decreased by 2.33°C to fit the range of the archaeological data. Model C (yellow triangles) was created using the summer average and one winter value of  $\delta^{18}O_{H2O}$  for Pigeon Creek (Table 4.1) and the minimum winter temperatures had to be decreased by 3.32°C and the maximum summer temperatures had to be increased by 0.28°C to fit the range of the archaeological data.

range of the archaeological data (Model B; Figure 5.5). The third hypothetical model assumed that the  $\delta^{18}O_w$  changes seasonally, but that the change was constant throughout modern and archaeological time periods. Using the summer average of south Pigeon Creek and the one winter  $\delta^{18}O_w$  value (Table 4.1), the winter minimum temperatures must be decreased by 3.32°C and the summer maximum temperatures must be increased by 0.28°C to fit the range of the archaeological data (Model C; Figure 5.5).

In summary, it is unlikely that only the  $\delta^{18}O_w$  was altered between archaeological and modern time periods, while the sea surface temperatures would have remained the same. Such a model would require the modern sea surface temperatures, the modern summer  $\delta^{18}O_w$  (0.89‰), and the winter  $\delta^{18}O_w$  to increase to 1.24‰, which is opposite to that observed where winter values get lower in  $\delta^{18}O$  and not higher. These findings, compiled with the archaeological data fit models (A-C; Figure 5.5), strongly suggest that winter, and possibly even summer, sea surface temperatures increased since archaeological times.

### **Sclerochronology and Stable Isotopes**

#### Modern shells – "Live" Specimens (PCL-UN2 & -BO2)

The  $\delta^{18}$ O profiles for the live specimens (PCL-UN2 and PCL-BO2) are compared to observed and calculated Bahamian sea surface temperature records in Figure 5.6. The range of computed isotopic sea surface temperatures were determined using measured  $\delta^{18}$ O values for carbonate, a  $\delta^{18}O_{water}$  value of 0.89‰, and the paleotemperature equation of Grossman and Ku (1986). A temperature shift of ~2.5°C was observed in each profile between the most positive  $\delta^{18}$ O values of consecutive years; between years one and two for PCL-UN2 and years two and three for PCL-BO2 (see Figure 5.6). A much smaller temperature shift of ~1.0°C was observed between the most negative  $\delta^{18}$ O values for the same consecutive years. These temperature shifts in the  $\delta^{18}O_{ar}$  correlate with temperature shifts of a similar degree in the historical record



**Figure 5.6.** The two top panels, A) PCL-UN2 and B) PCL-BO2, are correlated with the Bahamian temperature record (panel C). Dotted lines connect shell deposited over a particular time interval. Numbers in panels A and B represent approximate age. The orange boxes highlight the  $\delta^{18}$ O value recorded at the time of collection on June 2000. The blue line in panel C represents the lower temperature limit predicted by the  $\delta^{18}$ O values from the live specimens (PCL-UN2 and PCL-BO2) profiles. Red and pink squares and green diamonds are the same as in Figures 4.2 and 4.3.

(panel C.; Figure 5.6). Furthermore, the entire isotopic profile of PCL-UN2 is ~2°C lower than the profile of PCL-BO2 (panels A and B; Figure 5.6). This suggests that the  $\delta^{18}O_{water}$  may have been slightly different or even the temperatures slightly different, but in a consistent way over these two years. Conclusively, the temperatures calculated for the live specimens (PCL-UN2 and PCL-BO2) fit within the range of the Bahamian record indicating that seasonality is accurately recorded in the  $\delta^{18}O$  profiles of modern *Codakia orbicularis*.

After determining the oxygen isotope cycles, the calculation of age was straightforward. The shell height was determined for the first two years to be ~15-21mm and ~30-35mm, respectively, from the growth curves of Berg and Alatalo (1984). These distances established a starting point for the determination of approximate ages for each specimen. Additionally, Berg and Alatalo (1984) calculated that shells reach approximately 30 millimeters in height at 2 years of age. For consistency, yearly markers for all specimens were identified as the most negative  $\delta^{18}$ O, and consequently the warmest summer temperature. Estimations of the ages for PCL-UN2 is approximately 2+ years old and PCL-BO2 is approximately 3+ years old based on the  $\delta^{18}$ O profiles (see Figure 5.6).

The age determination of PCL-UN2 was not without uncertainty given that  $\delta^{18}$ O values end on a cooling trend while those for PCL-BO2 suggest the exact opposite (see orange boxes in profiles; Figure 5.6 A., B.). This suggests that some shell growth is missing from the record of PCL-UN2. A comparison of the growth rates for the live specimens (PCL-UN2 and PCL-BO2) to Berg and Alatalo's (1984) data was made by plotting estimated height against age derived from the  $\delta^{18}$ O records (Figure 5.7). The similarity between the growth curves in this study and Berg and Alatalo (1984) indicated that the isotope-derived growth curve is probably accurate.



**Figure 5.7.** Growth rate model of *Codakia orbicularis* includes data from live specimens (PCL-UN2 and PCL-BO2) and articulated-dead specimens (PCM-UN21 and PCM-UN22) (Crystal Beach and Gold Rock Creek curves are modified from Berg and Alatalo, 1984).
#### Modern shells – Articulated Shells (PCM-UN21 & -UN22)

The articulated shells, or articulated-dead specimens, collected from the bottom of the lagoon, PCM-UN21 and PCM-UN22, were larger and probably had a longer life span; thus they provided additional information on seasonal growth when compared to records from live specimens (PCL-UN2 and PCL-BO2). The  $\delta^{18}$ O and computed sea surface temperatures for articulated-dead specimens (PCM-UN21 and PCM-UN22) are presented in Figures 4.4 A. and 4.5 A. Based upon visual observation, the seasonality in the articulated shell records is similar to that of the live specimens (see Table 4.3). The similarity in the fluctuating  $\delta^{18}$ O values for all four modern specimens suggests that *Codakia orbicularis* records accurate sea surface temperatures throughout its life. However, individual cycles in the isotope records of the articulated valves (PCM-UN21 and -UN22) cannot be correlated with cycles in the isotope records of the live specimens (PCL-UN2 and -BO2) since their shells were not deposited during coeval time periods. Additionally, while the cyclicity of the  $\delta^{18}$ O for articulated-dead specimens (PCM-UN21 and -UN22) is relatively stable over longer periods of time, some of the cycles were much harder to discern compared to those identified in the live specimens.

Following the previous procedure for determining age, PCM-UN21 was calculated to be 7+ years old and PCM-UN22 to be 8+ years old at the time of death (see Figures 4.4 A. and 4.5 A.). The estimated years of growth were plotted in Figure 5.7 and compared to the Berg and Alatalo (1984) growth rate curve. The growth curves for the articulated shells (PCM-UN21 and PCM-UN22) are indistinguishable from the growth curves from Berg and Alatalo (1984) and those for the live specimens (PCL-UN2 and PCL-BO2). The curve for PCM-UN21 deviates slightly in years 3 and 4, and this may be evidence that individual specimens of *Codakia orbicularis* grow at varying rates throughout their life histories, but they generally conform to a single model of growth.

#### Archaeological Shells

The  $\delta^{18}$ O profiles and computed sea surface temperatures for the archaeological specimens are presented in Figures 4.6 A. through 4.9 A. The archaeological  $\delta^{18}$ O records fluctuated irregularly over a wider range relative to the regular fluctuations over a lower and narrower range in the modern  $\delta^{18}$ O records. Following the previous procedure for determining age, PCA-6 was calculated to be 7+ years old, PCA-7 to be 7+ years old, PCA-9 to be 6+ years old, and PCA-10 to be 6+ years old at the time of death (see Figures 4.6 A-4.9 A). The estimated years versus the corresponding shell height were plotted in Figure 5.8. The growth curves for PCA-7 and PCA-9 are indistinguishable from the Berg and Alatalo (1984) growth curve, while the growth curves for PCA-6 and PCA-10 fall slightly below it. This deviation might have been the result of subjective age determination, but if the ages were overestimated for PCA-6 and -10, they would plot above the curve and then still fall below it.

Another possibility for the deviation from the Berg and Alatalo (1984) growth curve could be that specimens PCA-6 and -10 are from a different environment than PCA-7 and -9. These environments, either a different part of the lagoon or even a different island location, may have had limited food resources for the clams or some other factor that limited growth. However, the most probable explanation for the deviation from the Berg and Alatalo (1984) growth curve is that the sample size is not sufficient to accurately characterize variance in archaeological populations. A larger sample set is required to determine statistical differences among growth curve populations.

### Carbon

Average  $\delta^{13}$ C values for the specimens of this study ranged from 0.09 to 2.79‰ (Table 4.3). These  $\delta^{13}$ C values are much lower than the value calculated for aragonite deposited in equilibrium with the south Pigeon Creek water (~3.6‰). This equilibrium



**Figure 5.8.** Growth rate model of *Codakia orbicularis* includes data from archaeological shells (PCA-6, PCA-7, PCA-9, and PCA-10) (modified from Berg and Alatalo, 1984).

 $\delta^{13}$ C value for aragonite was calculated by adding the average  $\delta^{13}$ C value for DIC from south Pigeon Creek (~0.9‰) to the aragonite-bicarbonate enrichment factor (~2.7‰; Romanek et al., 1992). At the pH of seawater, there is only a small difference between the  $\delta^{13}$ C of DIC and HCO<sub>3</sub> at 25°C (0.2‰).

Shifts in the  $\delta^{13}$ C profiles may reflect the onset of spawning and sexual maturity for *Codakia orbicularis*. Romanek et al. (1987) found such a shift in the  $\delta^{13}$ C values for *Tridacna maxima* that corresponded with the onset of sexual maturity. Additionally, Romanek et al. (1987) and Krantz et al. (1987) showed a depletion of <sup>13</sup>C with age, opposite the trend observed in this study. However, there may be other factors, or maybe a combination of them that might effect the  $\delta^{13}$ C profile of a shell:

- Codakia might incorporate less metabolic carbon into its shell with the onset of sexual maturity and with age
- there may be a decrease in the production of metabolic carbon, possibly from a lack of or change in the food source
- Codakia might incorporate more <sup>13</sup>C into its shell as the rate of growth decreases

Shell height for the juvenile phase of growth for *Codakia* was approximated from Berg and Alatalo's (1984) growth curve and from their statement that sexual maturity occurred around the summer of the second year. Therefore, if a shift in  $\delta^{13}$ C should occur in *Codakia*, it would be expressed at a shell height of approximately 30 to 35mm. For specimens of this study, live specimen PCL-UN2 displayed a shift around 34mm before the summer of year two, live specimen PCL-BO2 showed a slight shift around 39mm after the summer of year two, and articulated-dead specimen PCM-UN21 displayed a distinct shift around 38mm after the summer of year two (Figures 4.2 B.-4.4 B.). The  $\delta^{13}$ C profile of articulated-dead specimen PCM-UN22 shifted to more positive values around 46mm near the summer of year three, but only four  $\delta^{13}$ C values had been measured for the juvenile phase of growth (Figures 4.5 B.). If the shift represents the onset of sexual reproduction, then PCM-UN22 would have matured approximately one year later than the other three specimens. Summarily, the  $\delta^{13}$ C shifts for the modern specimens provide evidence that carbon isotope profiles record the onset of spawning/sexual maturity.

Shifts in the  $\delta^{13}$ C of the archaeological records are much harder to discern. The sampling strategy for archaeological specimen PCA-6 may have included only the adult phase of growth, while archaeological specimens PCA-7 and PCA-9 show little difference in  $\delta^{13}$ C over the period where *Codakia* reaches sexual maturity (Figures 4.6 B.-4.8 B.). Unlike the other three specimens, archaeological specimen PCA-10 has a well defined shift around 31mm in the summer of year two, which corresponds to the little  $\delta^{13}$ C shifts in PCA-7, PCA-9, and those in the modern specimens (Figures 4.9 B.). The lack of a prominent shift in PCA-7 and PCA-9 could be due to the onset of sexual maturity prior to a shell height of 28mm, although additional samples must be collected to determine this.

The relatively low average  $\delta^{13}$ C values for *Codakia orbicularis* may be the result of either or both of the following factors:

- 1) the  $\delta^{13}$ C for DIC measured from Pigeon Creek seawater is not characteristic of the DIC that is utilized used by *Codakia*
- there is a component of metabolic carbon, depleted in <sup>13</sup>C with respect to seawater that is mixing with the pallial fluid.

Additionally, there is a general trend of increasing  $\delta^{13}$ C average with shell height (see Table 4.3). This trend indicates that *Codakia orbicularis* incorporates more <sup>13</sup>C in aragonite as it ages. Based on these results, a mixture of metabolic carbon and ambient environmental carbon is most likely being incorporated into the shell of *Codakia orbicularis*.

#### Dark increments

"Dark" increments previously identified in Figures 4.2 A. to 4.9 A. are examined in this section. The "disturbance" increments reflect minor environmental disturbances (Jones et al., 1989) and do not correlate with any periodic event based upon visual observations of the isotopic records for *Codakia*. The number of dark increments for each modern and archaeological specimen, the number of cycles in each isotopic record, and the corresponding height in millimeters are listed in Table 5.1. Based upon visual observation, no relationship was observed between a dark increment and  $\delta^{18}$ O or  $\delta^{13}$ C value, nor the total number of dark bands and isotopic cycles and shell height. No obvious pattern could be found either in the distance between each dark increment and shell height or in the number of growth increments between dark increments.

The only correlation that could be made was in the modern specimens. For these specimens, the number of dark increments increased with the number of cycles in the  $\delta^{18}$ O records (see Table 5.1). Additionally, the number of dark increments increased as the shell height increased. However, a larger sample set is required to determine if these initial correlations are meaningful.

Neither dark increments nor disturbance increments can be used to determine the age of a *Codakia* specimen. These findings support the possibility that the random occurrence of dark increments on the shell is probably due to the continuous nutrition the clam receives from symbiotic bacteria (Alatalo, 2000). However, these findings do not support Mitchell (1983), who suggests that dark increments represent an annual winter break in shell growth.

#### **Archaeological Significance**

### Season of Capture

Archaeologists are interested in determining season of capture of molluscs,

		Number of cycles in the isotopic record	Total number of dark increments	Height
	PCL-UN2	1	4	39.49
Modern	PCL-BO2	2	5	57.12
	PCM-UN21	5	7	79.88
	PCM-UN22	5	7	81.37
	PCA-6	5	15	74.61
Archaeological	PCA-7	5	9	72.90
	PCA-9	4	7	66.76
	PCA-10	4	8	59.40

**Table 5.1.** The number of cycles found identified in the  $\delta^{18}$ O record, the number of dark increments found on the shell surface, and the maximum height of each specimen.

since these results provide inferences about eating habits and site occupation. Season of capture might be determined by counting the number of dark increments, as these were suggested to represent winter breaks in shell growth, on the shell surface of *Codakia orbicularis* (Mitchell, 1983). However, the isotopic records of *Codakia orbicularis* in this study did not verify that the dark increments represented yearly winter breaks. Additionally, no cyclical seasonal pattern could be found within the population of clams analyzed in this study.

A more reliable method of determining season of capture is by using the oxygen isotope record (Shackleton, 1973; Clark, 1979; Killingley and Berger, 1979; Killingley, 1981; Deith, 1983; 1986; Quitmyer, Jones, and Arnold, 1997)). However, caution must be practiced even when using the  $\delta^{18}$ O records to determine season of capture. Alone, the  $\delta^{18}$ O value for the lip on live specimen PCL-UN2 suggested a winter capture as the  $\delta^{18}$ O values were trending to more positive values, but this particular clam was collected in summer of 2000. Alternatively, live specimen PCL-BO2 showed a trend of decreasing  $\delta^{18}$ O in the cycle closest to the shell margin, which accurately reflected the time of capture. As previously discussed, live specimen PCL-UN2 may have experienced a growth cessation which would explain the positive trend at the end of the isotopic record. If no growth cessations occurred at the end of the lives of the articulated shells (PCM-UN21 and PCM-UN22), then the season of death can be determined to be summer and winter, respectively. Collectively, more data is necessary to determine if shell edges are a reliable recorder of season of capture.

The archaeological specimens of *Codakia* were found in a large heap at the Pigeon Creek site and archaeologists are interested in knowing if this heap was generated as a single harvesting event, as currently believed (Berman, 2001). However, more modern specimens must be analyzed, specifically along the shell edge, to get a robust data set before interpretations can be made on when *Codakia orbicularis* was most likely to be collected by the Lucayans.

#### Climate shift

The ranges and maximum values of  $\delta^{18}$ O are distinct for the archaeological and modern specimens. More specifically, the modern and archaeological  $\delta^{18}$ O records would look similar if not for the more positive maximum values of the archaeological specimens. The results of the t-test, which found a significant difference between the means of the modern and archaeological groups (Table 4.5.), support this isotopic shift from the archaeological to the modern times. The significant difference of the means implies that the modern group and the archaeological group are either from different island environments or different climates.

Furthermore, the model-calculated fits of the archaeological data (Figure 5.5) indicate that winter, and possibly summer, sea surface temperatures were lower during the period of occupation, assuming the  $\delta^{18}$ O of seawater was invariant. The descriptive statistics, the t-test results, and the calculated models (A-D) are all consistent with to the conclusions of Nyberg et al. (1999), who found that the time period of the Little Ice Age experienced a decrease in the winter sea surface temperatures and an increase in seasonal variability for the northeastern Caribbean.

In addition to a shift in the sea surface temperatures, humidity may have increased, which may also be interpreted as an increase in rainfall, surrounding the period of occupation at Pigeon Creek (Berman and Gnivecki, 1995; Curtis et al., 1996). Since no effect of rainfall could be found in the modern  $\delta^{18}$ O isotopic records, a comment cannot be made on the effect of rainfall on the isotopic profiles.

While it still remains possible for the archaeological samples to have originated in an island environment different than that of modern south Pigeon Creek, the archaeological data most likely reflect a climate shift from the modern. A more robust collection of specimens of *Codakia orbicularis* and water samples from an assortment of island environments, including additional work at Pigeon Creek, is necessary. Assuming *Codakia orbicularis* precipitated its shell in isotopic equilibrium since archaeological times, the combination of factors in this study are all compatible with the conclusion that the isotopic shift is climatically derived. Summarily, the period of occupation ( $380 \pm 40$  <sup>14</sup>C BP) on San Salvador Island probably experienced cooler winters and slightly cooler average temperatures than the modern.

#### **CHAPTER 6**

#### CONCLUSIONS

These numbered conclusions correspond to the numbered research hypotheses formulated in the Introduction.

- 1) The  $\delta^{18}$ O from all four modern specimens fit within the boundaries of an oxygen isotope model demonstrating that infaunal *Codakia orbicularis* precipitates its shell in equilibrium with surrounding seawater. Additionally, *Codakia orbicularis* accurately records seasonality as demonstrated by the correlation of the computed sea surface temperatures for 'live' specimens PCL-UN2 and PCL-BO2 and the historical sea surface temperature record.
- 2) The growth rates estimated by cycles within the δ<sup>18</sup>O records of the four modern *Codakia* are similar to the growth rate computed using the Berg and Alatalo (1984) age-class determination. Comparatively, the growth rates from the four archaeological specimens start off along the growth curve determination by Berg and Alatalo (1984) but some specimens (PCA-6 and -7) diverge from it over time. This deviation may suggest acceleration in the growth rate from archaeological to modern times. Alternatively, the variability in the growth rates of the archaeological specimens may be related to the environment in which they lived.
- 3) No seasonality could be observed in the carbon isotopic profiles. However, shifts in the  $\delta^{13}$ C records do occur for some of the specimens and may reflect the onset of spawning and sexual maturity for *Codakia orbicularis*.
- 4) The dark increments of *Codakia orbicularis* do not appear to represent winter breaks and therefore they cannot be used to determine neither the age nor the season of capture.

- 5) More modern specimens of *Codakia* shells need to be analyzed before interpretations can be made regarding season of capture.
- 6) The  $\delta^{18}$ O values for the archaeological specimens from Pigeon Creek archaeological site have slightly more positive means and have more positive maximum  $\delta^{18}$ O values, which reflect a cooler climate than the modern. Additionally, ranges of the archaeological samples appear to be larger than the ranges of the modern samples. A t-test found a significant difference between the means of the modern and archaeological specimens. It can be inferred from these results that winters were cooler and average temperatures were slightly cooler on San Salvador Island around the period of occupation (380 ± 40 <sup>14</sup>C BP) relative to that of today.

#### **Future research**

To form more definite interpretations, a larger number of modern and archaeological specimens is required to produce a more robust data set. This robust data set would be used to verify the growth rate differences between modern and archaeological specimens observed in this study. A larger number of *Codakia* specimens is also needed to help quantify preliminary conclusions that d180 from shell margins accurately record season of capture. A larger number of archaeological specimens is needed to support the conclusion of a cooler climate for the period of occupation. Finally, more archaeological specimens must be analyzed to determine the popular season or seasons for collection of *Codakia* for food purposes.

With the advancements in sampling techniques, *Codakia* can be isotopically analyzed in the juvenile portion of the outer shell in a relatively short time frame. These additional analyses should provide a more complete isotopic record of *Codakia orbicularis* throughout ontogeny. Complete isotopic records of several specimens of *Codakia* would then be used to verify that the shifts in  $\delta^{13}$ C values across carbon isotope profiles represent the transition from a juvenile to an adult phase of growth.

Further work is necessary to better constrain the environmental effects on the isotopes of *Codakia orbicularis*. Monthly sea surface temperatures should be collected at Pigeon Creek to replace the estimated monthly sea surface temperatures used to create the model. Finally, a collection of isotopes from *Codakia* from an assortment of island environments and water depths would demonstrate the isotopic ranges of *Codakia orbicularis*.

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APPENDICES

### APPENDIX A

### **REPLICATES AND STANDARDS**

**Appendix A.1.** Replicate data for about 10% of the  $\delta^{13}$ C and  $\delta^{18}$ O data. The average and difference between the original data and the replicate data are listed in two columns to the right of the data; at the bottom of these two columns, a summary of descriptive statistics is shown for each specimen.

		δ13	С			$\delta^{_{18}}$	0	
	1 <sup>st</sup> Run	Reps	Ave.	Diff.	1 <sup>st</sup> Run	Reps	Ave.	Diff.
PCL-UN2	1.21	1.07	1.14	0.14	-0.28	-0.73	-0.50	0.45
I CL-UNZ	1.17	0.93	1.05	0.24	0.22	-0.27	-0.02	0.50
		Mean	1.09	0.19		Mean	-0.26	0.47
		St. Dev.	0.06	0.07		St. Dev.	0.34	0.04
		Max	1.14	0.24		Max	-0.02	0.50
		Min	1.05	0.14		Min	-0.50	0.45
	1.22	1.47	1.34	0.25	0.53	0.86	0.69	0.33
	0.89	0.97	0.93	0.08	-0.12	-0.18	-0.15	0.06
	0.55	0.52	0.53	0.03	-1.07	-1.11	-1.09	0.04
PCL-BO2	1.22	1.21	1.22	0.01	-0.35	-0.22	-0.29	0.13
	1.55	2.28	1.92	0.73	-1.52	-0.73	-1.13	0.79
	1.87	1.84	1.86	0.03	-1.15	-1.23	-1.19	0.08
	1.09	1.55	1.32	0.46	-1.17	-0.87	-1.02	0.30
-		Mean	1.30	0.23		Mean	-0.60	0.25
		St. Dev.	0.49	0.28		St. Dev.	0.71	0.27
		Max	1.92	0.73		Max	0.69	0.79
		Min	0.53	0.01		Min	-1.19	0.04
	2.22	1.91	2.06	0.31	0.73	-0.17	0.28	0.90
	2.92	2.96	2.94	0.04	0.36	0.12	0.24	0.24
	2.97	2.92	2.94	0.05	0.01	-0.55	-0.27	0.56
	2.92	2.64	2.78	0.27	-0.27	-1.02	-0.64	0.75
PCM-UN21	2.69	2.32	2.50	0.37	0.13	-0.28	-0.07	0.41
1 011-01121	2.45	2.21	2.33	0.24	0.11	0.09	0.10	0.02
	1.28	1.01	1.15	0.27	-0.48	-0.94	-0.71	0.46
	2.72	2.37	2.54	0.34	0.19	-0.26	-0.04	0.45
	2.75	2.73	2.74	0.02	-0.06	0.43	0.18	0.49
	2.45	2.27	2.36	0.18	0.14	-0.15	0.00	0.29
		Mean	2.43	0.21		Mean	-0.09	0.46
		St. Dev.	0.53	0.13		St. Dev.	0.35	0.25
		Max	2.94	0.37		Max	0.28	0.90
		Min	1.15	0.02		Min	-0.71	0.02

Appendix A.1. Continued.

		$\delta^{13}$	С			$\delta^{_{18}}$	0	
	1 <sup>st</sup> Run	Reps	Ave.	Diff.	1 <sup>st</sup> Run	Reps	Ave.	Diff.
	2.64	1.97	2.30	0.67	1.25	0.24	0.74	1.01
	3.15	2.65	2.90	0.50	0.04	-0.72	-0.34	0.76
	3.11	2.35	2.73	0.76	1.24	0.39	0.81	0.85
	2.72	2.26	2.49	0.46	0.42	-0.33	0.05	0.75
	3 52	3.29	3.40	0.23	-0.17	-0 55	-0.36	0 38
PCM-UN22	3 04	$2.2^{\circ}$	2 72	0.64	1.06	-0.21	0 43	1 27
	3 36	2.40	3 08	0.04	1.00	0.21	0.73	$0.52^{+}$
	2.50	2.00	) 76	0.50	0.97	0.40	0.74	0.52 0.41
	2.70	2.33	2.70	0.43	0.07	0.40	0.00	1.02
	3.40	2.30 2.45	3.02 2.74	0.00	0.82	-0.21	0.30	1.03
	2.84	2.03	2.14	0.19	0.79	0.40	0.03	0.33
		wiean	2.82	0.33		wiean	0.3/	0.73
		St. Dev.	0.31	0.22		St. Dev.	0.44	0.32
		Max	3.40	0.88		Max	0.81	1.27
		Min	2.30	0.19		Min	-0.36	0.33
PCA-6	1.95	2.09	2.02	0.14	-0.11	0.13	0.01	0.24
		Mean	N	/A	•	Mean	N	/A
		St. Dev	N	/A		St. Dev.	N	Ά/Α
		Max	N	/A		Max	N/	Ά
		Min	N	/A		Min	NL	'A
		141111	1 N			141111	1 N/	4 <b>A</b>
	1.01	0.86	0.93	0.15	-0.63	-0.74	-0.68	0.11
	2.29	1.71	2.00	0.58	0.24	-0.11	0.07	0.35
PCA-9	1.99	1.33	1.66	0.66	0.49	-0.08	0.20	0.57
	2.67	2.00	2.33	0.67	0.70	0.42	0.56	0.28
	1.27	0.70	0.98	_0.57	-0.61	-0.75	-0.68	_0.14
		Mean	1.58	0.53	_	Mean	-0.11	0.29
		St. Dev.	0.62	0.22		St. Dev.	0.55	0.18
		Max	2.33	0.67		Max	0.56	0.57
		Min	0.93	0.15		Min	-0.68	0.11
[]	-1 09	-1 44	-1.26	0 35	0 33	-0 44	-0.05	0 77
	1 55	2 40	1.20	0.85	1 25	-0.28	0.05	1 53
	1.55	3 10	2 32	1 56	1.25	0 43	1 14	1 43
	1.54	1 75	1 81	0.12	0.41	-0.49	-0.02	0 80
PCA 10	1.07	1.75	1 25	0.12 0.42	_1 22	-0.+0 _1 76	_1 20	0.09
1 CA-10	1.14 2.15	1.50	1.33	0.42	-1.55	-1.20 1.20	-1.30	1 10
	2.13	1.4ð 1.75	1.01	0.0/	-0.20	-1.38	-0./9 1.25	1.10
	1.37	1.70		0.18	1.24	1.20	1.23	0.02
	2.29	1./8	2.04	0.51	0.8/	-0.42	0.22	1.29
	1.90	2.06	1.98	0.16	-0.20	0.18	-0.01	0.38
		Mean	1.52	0.54		Mean	0.10	0.84
		St. Dev.	1.08	0.45		St. Dev.	0.82	0.57
		Max	2.32	1.56		Max	1.25	1.53
		Min	-1.26	0.12		Min	-1.30	0.02

DAY	C-13	STDEV	0-18	STDEV
	2.32	0.08	40.32	0.05
	2.37	0.02	40.27	0.07
1	2.35	0.05	39.12*	0.10
	2.27	0.04	40.13	0.07
	0.04	0.05	0.1	0.1
	2.04	0.05	39.97	0.01
	1.95	0.08	39.94	0.09
	2.06	0.06	39.96	0.02
	2.06	0.05	39.93	0.03
	2.26	0.05	40.06	0.01
2	2.26	0.02	39.99	0.06
2	2.10	0.05	39.75	0.05
	2.20	0.06	39.88	0.04
	2.18	0.05	39.91	0.02
	2.21	0.10	40.01	0.02
	2.16	0.05	40.08	0.01
	0.1	0.1	0.1	0.03
	2.25	0.02	39.49	0.10
	2.34	0.02	39.71	0.01
	2.25	0.07	39.49	0.09
	2.25	0.13	39.78	0.09
	2.47	0.13	39.79	0.16
3	2.41	0.06	39.73	0.08
	2.31	0.03	39.72	0.06
	2.34	0.05	39.61	0.01
	2.26	0.05	39.52	0.03
	2.25	0.01	39.62	0.04
	0.1	0.1	0.1	0.1
	2.25	0.09	39.18	0.08
	2.35	0.08	39.36	0.09
	2.22	0.10	39.21	0.11
1	2.19	0.04	39.11	0.04
4	2.00	0.14	38.92	0.13
	2.58	0.06	39.64	0.11
	2.17	0.08	39.08	0.11
	0.2	0.1	0.2	0.1
	2.30	0.05	39.40	0.08
	2.25	0.03	39.41	0.05
	2.38	0.09	39.59	0.02
	2.21	0.01	39.27	0.05
	2.45	0.05	39.58	0.07
5	2.33	0.15	39.45	0.02
	2.25	0.08	39.34	0.10
	2.49	0.21	39.65	0.07
	2.23	0.08	39.39	0.08
	2.26	0.07	39.39	0.05
	0.1	0.1	0.1	0.1
AVERAGE	0.1		0.1	

Appendix A.2. Precision of the standards for each day or session of isotopic analysis.

# APPENDIX B ISOTOPE DATA

**Appendix B. 1.** Increment number, carbon and oxygen isotope data, distance of increment down the shell (mm), and calculated water paleotemperature (°C) for specimen PCL-UN2.

Increment #	$\delta^{_{13}}C$	$\delta^{_{18}}\mathbf{O}$	mm	T <sup>•</sup> C
1	0.39	0.79	17.00	22.27
2	0.05	0.41	17.47	24.07
3	0.04	0.22	17.80	24.96
4	0.16	0.46	18.33	23.82
5	-0.15	-0.17	18.63	26.78
6	-0.12	-0.07	18.99	26.29
7	0.02	-0.61	19.40	28.82
8	-0.29	-0.52	19.80	28.44
9	-0.33	-0.64	20.38	28.98
10	0.01	-0.68	20.70	29.15
11	-0.14	-0.55	20.80	28.53
12	-0.38	-0.68	21.09	29.14
13	-0.48	-0.57	21.43	28.63
14	-0.41	-0.67	21.64	29.13
15	-0.02	-0.50	21.85	28.34
16	-0.20	-0.42	22.18	27.96
17	-0.19	-0.32	22.64	27.46
18	-0.09	-0.50	23.00	28.32
19	-0.02	-0.45	23.53	28.07
20	-0.24	-0.58	23.78	28.72
21	-0.31	-0.69	23.92	29.20
22	-0.16	-0.47	24.41	28.18
23	-0.15	-0.48	24.87	28.20
24	-0.19	-0.53	25.40	28.48
25	-0.06	-0.49	26.39	28.26
26	0.07	-0.43	26.88	27.97
27	0.19	-0.35	27.31	27.63
28	0.22	-0.45	27.53	28.08
29	0.29	-0.15	28.15	26.67
30	-0.11	-0.38	28.66	27.78
31	-0.35	-0.47	29.21	28.16
32	-0.02	0.05	29.68	25.75
33	0.10	0.14	30.30	25.32
34	0.14	-0.12	30.82	26.52
35	-0.03	0.07	31.43	25.65
36	0.19	0.31	31.92	24.53
37	0.21	0.24	32.58	24.85
38	0.05	0.04	33.10	25.78
39	0.36	0.38	33.64	24.20
40	0.65	0.26	34.18	24.76
41	1.25	0.22	34.63	24.93
42	0.45	-0.50	35.08	28.31

# Appendix B. 1. Continued.

43	0.11	-0.65	35.58	29.00
44	0.05	-0.90	36.15	30.22
45	0.31	-0.62	36.74	28.88
46	0.46	-0.94	37.33	30.37
47	0.91	-0.91	37.93	30.24
48	1.21	-0.28	38.30	27.29
49	1.17	0.22	39.33	24.92

Increment #	$\delta^{_{13}}C$	$\delta^{_{18}}\mathbf{O}$	mm	T <sup>•</sup> C
1	0.83	-0.20	24.64	26.93
3	1.20	0.33	25.73	24.43
5	1.22	0.53	27.09	23.50
7	1.02	0.32	28.03	24.46
9	0.89	-0.12	28.60	26.54
11	0.68	-0.04	29.54	26.15
13	0.73	-0.08	30.79	26.36
15	0.52	-0.32	32.23	27.48
17	0.19	-1.37	33.63	32.38
19	0.51	-0.99	34.73	30.60
21	0.55	-1.07	36.32	31.00
23	0.19	-1.12	37.58	31.25
25	0.22	-0.35	38.54	27.62
27	1.51	-0.44	39.93	28.05
28	1.18	-0.08	40.53	26.34
30	0.86	-0.03	41.71	26.12
32	1.22	-0.35	43.44	27.62
34	0.84	-0.87	44.49	30.04
36	0.91	-1.31	46.18	32.14
38	1.55	-1.52	47.90	33.11
39	1.48	-1.41	48.09	32.59
41	1.87	-1.15	49.83	31.38
43	1.45	-1.40	50.90	32.52
45	1.89	-0.42	52.04	27.95
46	1.09	-1.17	52.19	31.48
47	1.72	-0.17	52.97	26.79
49	1.02	-0.34	54.42	27.58
50	1.60	-0.61	56.23	28.84
51	1.37	-0.93	56.44	30.32

**Appendix B. 2.** Increment number, carbon and oxygen isotope data, distance of increment down the shell (mm), and calculated water paleotemperature (°C) for specimen PCL-BO2.

Increment #	$\delta^{13}C$	$\delta^{_{18}}\mathbf{O}$	mm	T <sup>•</sup> C
1	1.39	-0.23	25.58	27.06
2	1.32	-0.38	26.35	27.74
3	2.14	-0.44	26.81	28.04
5	1.43	-0.63	27.94	28.95
7	1.60	-0.97	29.18	30.50
9	2.03	-0.46	30.59	28.11
11	1.40	-1.01	31.68	30.70
13	2.01	0.45	33.64	23.87
15	2.22	0.73	35.16	22.56
17	2.02	0.51	36.38	23.56
19	2.07	0.31	37.77	24.52
21	2.40	-0.30	38.81	27.38
23	2.95	-0.41	40.13	27.88
25	2.97	-0.63	41.10	28.91
27	2.92	0.36	42.69	24.30
29	2.86	0.67	44.27	22.84
31	2.46	0.30	45.92	24.56
33	2.97	0.01	46.43	25.92
35	1.84	-0.72	47.88	29.37
37	2.92	-0.27	49.05	27.23
39	2.85	-0.02	51.05	26.05
41	2.90	0.55	52.57	23.39
43	2.94	0.04	54.71	25.79
45	2.93	0.17	56.36	25.19
47	2.57	0.36	57.62	24.30
49	1.97	0.07	58.79	25.66
51	3.00	0.18	60.40	25.12
53	2.69	0.13	61.66	25.35
55	3.18	0.21	62.51	24.97
56	3.40	0.19	62.96	25.09
58	2.93	0.36	64.75	24.30
60	2.45	0.11	66.92	25.47
62	1.28	-0.48	68.62	28.23
63	2.04	-0.37	69.61	27.72
65	2.72	0.19	71.40	25.10
67	2.32	0.18	72.90	25.14
69	1.73	-0.58	74.20	28.68
71	2.75	-0.06	76.66	26.26
73	2.45	0.14	78.48	25.30
74		-0.60	79.18	28.79

**Appendix B. 3.** Increment number, carbon and oxygen isotope data, distance of increment down the shell (mm), and calculated water paleotemperature (°C) for specimen PCM-UN21.

Increment #	$\delta^{_{13}}C$	$\delta^{_{18}}\mathbf{O}$	mm	T <sup>•</sup> C
1	2.02	-0.32	31.16	27.47
9	1.85	-0.28	35.81	27.29
13	0.75	-0.17	38.69	26.75
17	1.38	0.30	42.33	24.57
25	1.93	-0.51	47.95	28.37
27	2.12	-0.25	49.35	27.17
29	2.21	-0.34	50.59	27.56
31	2.64	0.75	52.25	22.47
33	2.42	-0.27	54.24	27.26
35	2.45	0.29	55.75	24.63
37	2.41	0.24	57.15	24.86
39	2.70	0.48	58.58	23.74
41	2.63	-0.03	60.37	26.10
42	2.79	-0.09	60.89	26.39
43	2.29	-0.43	61.18	27.97
44	2.70	-0.36	62.20	27.66
45	3.15	-0.46	62.96	28.15
46	3.55	-0.07	63.37	26.29
47	2.82	0.09	64.25	25.54
48	3.11	0.74	65.01	22.51
49	2.88	0.76	65.86	22.42
50	2.78	0.59	66.55	23.22
51	2.72	-0.08	67.47	26.33
52	3.29	-0.16	68.35	26.71
53	3.46	-0.18	69.18	26.83
54	3.32	-0.24	69.73	27.11
55	3.13	-0.53	70.28	28.47
56	3.52	-0.65	70.66	29.04
57	3.52	-0.67	71.09	29.13
58	3.28	-0.11	71.83	26.49
59	2.67	0.35	72.23	24.33
60	3.04	0.56	72.51	23.33
61	3.36	0.50	72.63	23.63
62	3.18	0.05	73.41	25.73
63	3.77	0.25	74.46	24.82
64	3.13	-0.36	74.60	27.64
65	4.04	0.22	75.12	24.96
66	3.51	0.52	75.37	23.53
67	2.99	0.53	75.97	23.49
68	2.98	0.37	76.84	24.24
69	2.95	0.28	77.47	24.64

**Appendix B. 4.** Increment number, carbon and oxygen isotope data, distance of increment down the shell (mm), and calculated water paleotemperature (°C) for specimen PCM-UN22.

# Appendix B. 4. Continued.

70	3.46	0.32	78.20	24.48
71	3.11	0.25	78.70	24.78
72	3.48	-0.01	79.11	26.04
73	2.70	-0.44	79.65	28.05
74	2.84	0.29	80.66	24.61
75	2.55	0.32	81.07	24.48

**Appendix B. 5.** Increment number, carbon and oxygen isotope data, distance of increment down the shell (mm), and calculated water paleotemperature (°C) for specimen PCA-6.

Increment #	δ <sup>13</sup> C	δ18Ο	mm	ТС	
1	2.41	0.18	30.00	25.14	
4	1.95	-0.11	31.42	26.48	
6	2.81	0.16	32.87	25.22	
9	2.19	-0.10	34.10	26.43	
11	2.01	-0.01	35.62	26.00	
13	1.90	-0.03	37.73	26.11	
15	2.23	0.86	38.63	21.96	
17	2.12	0.67	40.52	22.82	
18	2.29	0.57	41.05	23.31	
20	1.77	-0.39	42.25	27.83	
21	2.44	-0.35	42.30	27.61	
22	2.43	-0.07	43.14	26.31	
23	2.93	0.04	43.54	25.76	
25	2.26	0.17	45.14	25.18	
27	2.37	0.63	46.28	23.03	
28	2.10	0.71	47.21	22.63	
30	2.83	0.52	48.35	23.52	
31	3.12	-0.16	48.63	26.74	
32	2.75	0.04	48.81	25.80	
33	3.17	0.15	48.97	25.29	
34	2.94	-0.13	49.03	26.60	
36	2.81	0.74	50.11	22.52	
37	2.08	0.60	50.27	23.17	
38	2.43	0.69	52.08	22.73	
39	2.39	0.71	52.41	22.64	
40	2.74	0.00	53.98	25.97	
41	2.71	-0.64	54.43	28.98	
42	2.71	-0.05	54.83	26.19	
44	2.98	0.57	55.93	23.30	
45	3.37	-0.14	56.50	26.64	
46	2.30	0.67	57.52	22.83	
47	3.16	0.10	58.08	25.50	
48	2.94	0.40	59.09	24.09	
50	2.28	1.11	60.27	20.77	
51	2.16	0.37	60.71	24.24	
52	3.04	0.15	61.61	25.28	
53	2.62	0.49	62.02	23.70	
54	3.18	1.15	62.44	20.58	
55	3.55	0.99	63.02	21.32	
57	2.71	0.74	64.06	22.51	
58	3.05	0.79	65.14	22.27	

# Appendix B. 5. Continued.

59	3.01	0.84	65.94	22.02
60	2.83	0.64	66.67	22.98
61	3.17	0.89	67.68	21.81
62	2.61	0.37	68.48	24.24
63	3.57	0.17	68.75	25.15
64	2.06	0.21	69.51	24.99
65	2.89	0.53	69.74	23.48
66		0.03	70.01	25.84
67	3.22	0.89	70.72	21.79
68	2.65	-0.24	71.34	27.11
69	3.54	1.02	72.09	21.18
70	2.75	0.65	72.37	22.91
71	2.53	0.45	72.51	23.88
72	2.41	0.43	73.60	23.97

94

**Appendix B. 6.** Increment number, carbon and oxygen isotope data, distance of increment down the shell (mm), and calculated water paleotemperature (°C) for specimen PCA-7.

Increment #	$\delta^{_{13}}C$	δ18Ο	mm	T <sup>•</sup> C
1	2.25	0.18	30.57	25.14
4	2.32	0.33	32.22	24.43
6	1.82	-0.12	33.65	26.54
8	1.96	-0.35	34.55	27.64
10	1.56	-0.17	35.66	26.76
12	0.96	-0.91	36.67	30.23
14	1.65	-0.70	37.41	29.26
16	2.41	0.32	38.2	24.48
17	2.47	0.48	38.89	23.72
18	2.51	0.13	39.24	25.38
20	2.32	0.42	40.74	24.00
22	1.80	-0.01	41.6	26.04
24	0.51	-0.95	42.51	30.45
25	1.26	-0.37	43.19	27.71
27	1.91	0.02	44.15	25.87
28	1.97	-0.94	44.66	30.36
30	1.86	-0.36	45.21	27.68
31	2.26	0.27	46.15	24.70
33	2.15	0.58	46.72	23.27
35	1.91	0.26	47.93	24.75
37	1.42	-0.29	49.28	27.32
39	1.33	-0.34	50.92	27.55
40	1.56	-0.19	51.54	26.87
41	2.32	-1.16	52	31.42
42	2.05	0.02	52.53	25.90
43	2.04	-0.25	52.8	27.14
45	1.94	0.44	54.3	23.90
47	2.22	0.35	56.49	24.35
49	2.33	0.18	57.58	25.13
50	2.46	0.33	57.81	24.41
52	2.83	0.37	59.53	24.25
53	2.57	0.21	60.23	25.01
55	2.56	-0.14	61.32	26.64
57	1.88	0.07	62.06	25.66
59	2.36	0.18	62.95	25.11
60	2.86	0.46	63.72	23.83
61	2.99	0.65	64.5	22.94
62	2.42	0.75	64.95	22.48
64	2.10	0.03	65.96	25.82
66	2.24	0.61	67.25	23.13
67	2.52	0.90	68.07	21.76

# Appendix B. 6. Continued.

68	2.11	0.77	68.78	22.34
69	1.88	0.72	69.6	22.61
70	1.40	-0.16	70.23	26.71
71		-0.88	70.7	30.11
72	2.97	1.01	72.39	21.23
73	1.77	0.17	72.54	25.16
**Appendix B. 7.** Increment number, carbon and oxygen isotope data, distance of increment down the shell (mm), and calculated water paleotemperature (°C) for specimen PCA-9.

Increment #	$\delta^{_{13}}C$	$\delta^{_{18}}\mathbf{O}$	mm	T <sup>•</sup> C
1	2.38	0.54	26.98	23.42
2	2.49	0.40	27.40	24.11
4	2.21	0.23	28.72	24.91
6	2.07	0.42	29.74	24.01
8	1.48	-0.14	30.92	26.61
10	1.45	-0.44	31.93	28.02
12	1.01	-0.63	33.14	28.92
14	1.05	-0.63	34.28	28.95
15	0.50	-0.96	34.78	30.46
16	1.88	-0.31	35.17	27.43
18	2.08	0.15	36.19	25.26
20	2.85	1.20	37.23	20.34
22	1.66	0.18	38.59	25.14
24	2.29	0.24	39.80	24.83
26	2.06	-0.53	41.00	28.48
27	1.64	-0.55	41.72	28.57
28	2.20	-0.21	42.13	26.94
30	1.94	-0.54	43.32	28.49
32	0.76	-1.58	44.58	33.38
34	2.17	-0.24	45.96	27.09
36	1.66	0.12	47.36	25.40
38	1.99	0.49	48.80	23.70
40	2.46	0.73	50.17	22.56
42	1.74	-0.49	51.36	28.26
44	1.92	-0.64	52.21	28.97
46	1.81	-0.19	53.62	26.85
48	1.80	-0.40	54.45	27.84
49	2.98	-0.63	54.85	28.91
51	2.66	-0.16	55.06	26.74
53	2.67	0.70	57.56	22.70
55	1.56	0.17	58.90	25.17
57	2.33	-0.44	60.38	28.06
59	2.77	-0.06	61.03	26.23
61	2.25	0.06	62.21	25.71
63	2.28	-0.11	63.39	26.51
65	1.56	-0.64	64.36	29.00
67	1.27	-0.61	64.70	28.83
68	2.16	0.49	65.14	23.67
69	2.39	-0.22	65.46	26.98
70	-0.01	-0.94	66.71	30.40

**Appendix B. 8.** Increment number, carbon and oxygen isotope data, distance of increment down the shell (mm), and calculated water paleotemperature (°C) for specimen PCA-10.

Increment #	δ <sup>13</sup> C	$\delta^{_{18}}O$	mm	T <sup>•</sup> C
1	0.88	0.37	25.53	24.22
3	-0.11	0.27	26.51	24.73
5	-0.70	0.69	27.40	22.74
7	-1.09	0.33	28.09	24.40
9	-1.05	0.51	29.05	23.60
11	0.28	-0.47	30.07	28.20
13	1.55	1.25	31.23	20.13
15	1.61	1.36	32.16	19.60
16	1.05	1.40	32.69	19.40
18	1.54	1.86	34.00	17.25
20	1.33	0.86	34.74	21.96
21	1.87	0.41	35.39	24.04
23	2.21	0.71	36.04	22.64
25	1.91	0.14	37.04	25.32
27	1.76	1.06	38.36	21.02
29	1.14	-1.33	40.23	32.22
31	1.50	-0.12	40.36	26.52
33	2.26	0.65	41.39	22.94
34	2.10	0.45	41.64	23.85
36	1.12	0.69	43.03	22.76
38	1.15	0.73	43.84	22.56
39	1.63	0.03	44.43	25.82
41	2.15	-0.20	45.46	26.92
43	2.96	-0.01	46.52	26.03
44	2.61	1.10	46.57	20.80
46	1.57	1.24	47.55	20.15
48	1.09	-0.60	48.22	28.81
49	2.23	-0.07	49.02	26.29
51	2.29	0.87	49.95	21.90
53	1.74	1.26	51.15	20.08
55	2.07	0.78	52.20	22.30
57	2.08	0.49	53.19	23.69
59	2.67	-0.15	54.02	26.68
61	2.87	1.47	55.06	19.09
63	1.58	0.31	56.10	24.52
65	1.90	-0.20	56.36	26.91
66	2.08	0.06	56.76	25.70
68	1.72	0.34	58.43	24.37
69	2.35	1.18	59.28	20.42

APPENDIX C STATISTICS

## Appendix C. 1. K-S test for PCL-UN2.

Data	Z-scores	Cum.Freq.	f(z)	d	
-0.94	-1.60	0.02	0.05	0.05	
-0.91	-1.53	0.04	0.06	0.04	
-0.90	-1.52	0.06	0.06	0.02	
-0.69	-0.99	0.08	0.16	0.10	
-0.68	-0.96	0.10	0.17	0.09	
-0.68	-0.96	0.12	0.17	0.07	
-0.67	-0.95	0.14	0.17	0.05	
-0.65	-0.89	0.16	0.19	0.05	
-0.64	-0.88	0.18	0.19	0.03	
-0.62	-0.82	0.20	0.21	0.03	
-0.61	-0.79	0.22	0.21	0.01	
-0.58	-0.74	0.24	0.23	0.01	
-0.57	-0.69	0.26	0.24	0.00	
-0.55	-0.64	0.28	0.26	0.00	
-0.53	-0.61	0.30	0.27	0.01	
-0.52	-0.59	0.32	0.28	0.02	
-0.50	-0.54	0.34	0.29	0.03	
-0.50	-0.53	0.36	0.30	0.04	
-0.50	-0.52	0.38	0.30	0.06	
-0.49	-0.50	0.40	0.31	0.07	
-0.48	-0.47	0.42	0.32	0.08	
-0.47	-0.45	0.44	0.32	0.10	
-0.47	-0.45	0.46	0.33	0.11	
-0.45	-0.40	0.48	0.34	0.12	
-0.45	-0.40	0.50	0.35	0.13	
-0.43	-0.35	0.52	0.36	0.14	
-0.42	-0.34	0.54	0.37	0.15	
-0.38	-0.25	0.56	0.40	0.14	
-0.35	-0.17	0.58	0.43	0.13	
-0.32	-0.08	0.60	0.47	0.11	
-0.28	0.01	0.62	0.50	0.10	
-0.17	0.27	0.64	0.61	0.01	
-0.15	0.33	0.66	0.63	0.01	
-0.12	0.41	0.68	0.66	0.00	
-0.07	0.53	0.70	0.70	0.02	
0.04	0.80	0.72	0.79	0.09	
0.05	0.81	0.74	0.79	0.07	
0.07	0.86	0.76	0.81	0.07	
0.14	1.04	0.78	0.85	0.09	
0.22	1.22	0.80	0.89	0.11	
0.22	1.24	0.82	0.89	0.09	
0.22	1.25	0.84	0.89	0.07	
0.24	1.29	0.86	0.90	0.06	
0.26	1.33	0.88	0.91	0.05	
0.31	1.45	0.90	0.93	0.05	
0.38	1.62	0.92	0.95	0.05	0.15 D
0.41	1.69	0.94	0.95	0.03	0.20 Critical D
0.46	1.82	0.96	0.97	0.03	
0.79	2.63	0.98	1.00	0.04	D <crit.daccept ho<="" td=""></crit.daccept>
49	n				····· <b>r</b> ·•

## Appendix C. 1. K-S test for PCL-BO2.

Data	<b>Z</b> -scores	Cum.Freq.	f(z)	d	
-1.52	-1.60	0.03	0.05	0.05	
-1.41	-1.41	0.07	0.08	0.05	
-1.40	-1.39	0.10	0.08	0.02	
-1.37	-1.34	0.13	0.09	0.01	
-1.31	-1.25	0.17	0.11	0.03	
-1.17	-1.02	0.20	0.15	0.01	
-1.15	-0.98	0.23	0.16	0.04	
-1.12	-0.93	0.27	0.18	0.06	
-1.07	-0.84	0.30	0.20	0.07	
-0.99	-0.70	0.33	0.24	0.06	
-0.93	-0.59	0.37	0.28	0.06	
-0.87	-0.49	0.40	0.31	0.06	
-0.61	-0.06	0.43	0.48	0.08	
-0.44	0.23	0.47	0.59	0.16	
-0.42	0.26	0.50	0.60	0.14	
-0.35	0.38	0.53	0.65	0.15	
-0.35	0.38	0.57	0.65	0.12	
-0.34	0.40	0.60	0.65	0.09	
-0.32	0.43	0.63	0.67	0.07	
-0.20	0.63	0.67	0.74	0.10	
-0.17	0.68	0.70	0.75	0.09	
-0.12	0.77	0.73	0.78	0.08	
-0.08	0.84	0.77	0.80	0.07	
-0.08	0.84	0.80	0.80	0.03	
-0.04	0.91	0.83	0.82	0.02	
-0.03	0.92	0.87	0.82	0.01	
0.32	1.52	0.90	0.94	0.07	
0.33	1.53	0.93	0.94	0.04	
0.53	1.87	0.97	0.97	0.04	
20	n				

100

D<Crit.D--accept Ho

0.25 Critical D

0.16 D

29 n

## Appendix C. 1. K-S test for PCM-UN21.

Data	Z-scores	Cum.Freq.	f(z)	d	
-1.01	-2.14	0.02	0.02	0.02	
-0.97	-2.04	0.05	0.02	0.00	
-0.72	-1.50	0.07	0.07	0.02	
-0.63	-1.30	0.10	0.10	0.02	
-0.63	-1.28	0.12	0.10	0.00	
-0.60	-1.22	0.15	0.11	0.01	
-0.58	-1.17	0.17	0.12	0.02	
-0.48	-0.95	0.20	0.17	0.00	
-0.46	-0.89	0.22	0.19	0.01	
-0.44	-0.86	0.24	0.20	0.02	
-0.41	-0.78	0.27	0.22	0.03	
-0.38	-0.72	0.29	0.24	0.03	
-0.37	-0.71	0.32	0.24	0.05	
-0.30	-0.54	0.34	0.29	0.02	
-0.27	-0.47	0.37	0.32	0.02	
-0.23	-0.39	0.39	0.35	0.02	
-0.06	-0.01	0.41	0.50	0.11	
-0.02	0.09	0.44	0.54	0.12	
0.01	0.16	0.46	0.56	0.12	
0.04	0.22	0.49	0.59	0.12	
0.07	0.28	0.51	0.61	0.12	
0.11	0.37	0.54	0.65	0.13	
0.13	0.43	0.56	0.67	0.13	
0.14	0.46	0.59	0.68	0.11	
0.17	0.51	0.61	0.69	0.11	
0.18	0.53	0.63	0.70	0.09	
0.18	0.54	0.66	0.71	0.07	
0.19	0.55	0.68	0.71	0.05	
0.19	0.55	0.71	0.71	0.03	
0.21	0.61	0.73	0.73	0.02	
0.30	0.81	0.76	0.79	0.06	
0.31	0.83	0.78	0.80	0.04	
0.36	0.93	0.80	0.82	0.04	
0.36	0.93	0.83	0.82	0.02	
0.36	0.93	0.85	0.83	0.00	
0.45	1.14	0.88	0.87	0.02	
0.51	1.29	0.90	0.90	0.02	0.13 D
0.55	1.37	0.93	0.92	0.01	0.21 Critical D
0.67	1.64	0.95	0.95	0.02	
0.73	1.77	0.98	0.96	0.01	D <crit.daccept ho<="" td=""></crit.daccept>
40	n				

## Appendix C. 1. K-S test for PCM-UN22.

Data	<b>Z</b> -scores	Cum.Freq.	f(z)	d	
-0.67	-1.81	0.02	0.04	0.04	
-0.65	-1.76	0.04	0.04	0.02	
-0.53	-1.45	0.06	0.07	0.03	
-0.51	-1.40	0.08	0.08	0.02	
-0.46	-1.28	0.10	0.10	0.02	
-0.44	-1.23	0.13	0.11	0.01	
-0.43	-1.19	0.15	0.12	0.01	
-0.36	-1.02	0.17	0.15	0.01	
-0.36	-1.01	0.19	0.16	0.01	
-0.34	-0.96	0.21	0.17	0.02	
-0.32	-0.92	0.23	0.18	0.03	
-0.28	-0.82	0.25	0.21	0.02	
-0.27	-0.80	0.27	0.21	0.04	
-0.25	-0.75	0.29	0.23	0.04	
-0.24	-0.72	0.31	0.24	0.06	
-0.18	-0.57	0.33	0.28	0.03	
-0.17	-0.53	0.35	0.30	0.03	
-0.16	-0.51	0.38	0.31	0.05	
-0.11	-0.39	0.40	0.35	0.03	
-0.09	-0.33	0.42	0.37	0.03	
-0.08	-0.30	0.44	0.38	0.04	
-0.07	-0.28	0.46	0.39	0.05	
-0.03	-0.18	0.48	0.43	0.03	
-0.01	-0.14	0.50	0.44	0.04	
0.05	0.02	0.52	0.51	0.01	
0.09	0.12	0.54	0.55	0.03	
0.22	0.44	0.56	0.67	0.13	
0.24	0.49	0.58	0.69	0.13	
0.25	0.51	0.60	0.70	0.11	
0.25	0.53	0.63	0.70	0.10	
0.28	0.61	0.65	0.73	0.10	
0.29	0.61	0.67	0.73	0.08	
0.29	0.63	0.69	0.73	0.07	
0.30	0.65	0.71	0.74	0.05	
0.32	0.70	0.73	0.76	0.05	
0.32	0.70	0.75	0.76	0.03	
0.35	0.78	0.77	0.78	0.03	
0.37	0.83	0.79	0.80	0.02	
0.48	1.10	0.81	0.86	0.07	
0.50	1.15	0.83	0.88	0.06	
0.52	1.21	0.85	0.89	0.05	
0.53	1.23	0.88	0.89	0.04	
0.56	1.31	0.90	0.91	0.03	
0.59	1.38	0.92	0.92	0.02	0.13 D
0.74	1.76	0.94	0.96	0.04	0.21 Critical D
0.75	1.78	0.96	0.96	0.02	
0.76	1.81	0.98	0.96	0.01	D <crit.daccept ho<="" td=""></crit.daccept>
47	n				

# Appendix C. 1. K-S test for PCA-6.

Data	<b>Z</b> -scores	Cum.Freq.	f(z)	d
-0.64	-2.37	0.02	0.01	0.01
-0.39	-1.79	0.04	0.04	0.02
-0.35	-1.68	0.05	0.05	0.01
-0.24	-1.42	0.07	0.08	0.02
-0.16	-1.24	0.09	0.11	0.04
-0.14	-1.18	0.11	0.12	0.03
-0.13	-1.17	0.13	0.12	0.01
-0.11	-1.10	0.14	0.14	0.01
-0.10	-1.08	0.16	0.14	0.00
-0.07	-1.02	0.18	0.15	0.01
-0.05	-0.96	0.20	0.17	0.01
-0.03	-0.92	0.21	0.18	0.02
-0.01	-0.86	0.23	0.19	0.02
0.00	-0.85	0.25	0.20	0.03
0.03	-0.78	0.27	0.22	0.03
0.04	-0.76	0.29	0.22	0.04
0.04	-0.74	0.30	0.23	0.06
0.10	-0.61	0.32	0.27	0.03
0.15	-0.50	0.34	0.31	0.01
0.15	-0.50	0.36	0.31	0.03
0.16	-0.47	0.38	0.32	0.04
0.17	-0.45	0.39	0.33	0.05
0.17	-0.43	0.41	0.33	0.06
0.18	-0.43	0.43	0.33	0.08
0.21	-0.35	0.45	0.36	0.07
0.37	0.03	0.46	0.51	0.07
0.37	0.03	0.48	0.51	0.05
0.40	0.10	0.50	0.54	0.06
0.43	0.16	0.52	0.57	0.07
0.45	0.21	0.54	0.58	0.07
0.49	0.30	0.55	0.62	0.08
0.52	0.39	0.57	0.65	0.10
0.53	0.41	0.59	0.66	0.09
0.57	0.50	0.61	0.69	0.10
0.57	0.50	0.63	0.69	0.09
0.60	0.57	0.64	0.72	0.09
0.63	0.64	0.66	0.74	0.10
0.64	0.67	0.68	0.75	0.09
0.65	0.70	0.70	0.76	0.08
0.67	0.74	0.71	0.77	0.08
0.67	0.75	0.73	0.77	0.06
0.69	0.79	0.75	0.79	0.00
0.071	0.84	0.75	0.80	0.05
0.71	0.84	0.79	0.80	0.03
0.74	0.04	0.80	0.82	0.03
0.74	0.90	0.82	0.82	0.03
0.79	1.03	0.82	0.85	0.03
0.84	1.05	0.86	0.88	0.03
0.86	1.18	0.88	0.88	0.02

## Appendix C. 1. PCA-6 Continued.

0.89	1.26	0.89	0.90	0.02	
0.89	1.27	0.91	0.90	0.00	
0.99	1.51	0.93	0.93	0.02	0.10 D
1.02	1.58	0.95	0.94	0.01	0.20 Critical D
1.11	1.79	0.96	0.96	0.02	
1.15	1.88	0.98	0.97	0.01	D <crit.d-accept ha<="" td=""></crit.d-accept>
55	n				

## Appendix C. 1. K-S test for PCA-7.

Data	<b>Z-scores</b>	Cum.Freq.	f(z)	d	
-1.16	-2.38	0.02	0.01	0.01	
-0.95	-1.97	0.04	0.02	0.00	
-0.94	-1.94	0.06	0.03	0.02	
-0.91	-1.89	0.08	0.03	0.03	
-0.88	-1.84	0.10	0.03	0.05	
-0.70	-1.48	0.13	0.07	0.04	
-0.37	-0.84	0.15	0.20	0.08	
-0.36	-0.83	0.17	0.20	0.06	
-0.35	-0.81	0.19	0.21	0.04	
-0.34	-0.77	0.21	0.22	0.03	
-0.29	-0.68	0.23	0.25	0.04	
-0.25	-0.60	0.25	0.27	0.04	
-0.19	-0.49	0.27	0.31	0.06	
-0.17	-0.44	0.29	0.33	0.06	
-0.16	-0.43	0.31	0.33	0.04	
-0.14	-0.40	0.33	0.35	0.03	
-0.12	-0.35	0.35	0.35	0.03	
-0.01	-0.15	0.38	0.30	0.09	
0.01	-0.09	0.30	0.44	0.09	
0.02	-0.09	0.40	0.40 0.47	0.07	
0.02	-0.06	0.42	0.47 0.48	0.07	
0.05	0.00	0.44	0.40	0.00	
0.07	0.13	0.40	0.50	0.07	
0.15	0.22	0.40	0.55	0.07	
0.17	0.22	0.50	0.59	0.11	
0.18	0.22	0.52	0.59	0.09	
0.18	0.23	0.54	0.59	0.07	
0.18	0.24	0.50	0.59	0.05	
0.21	0.28	0.58	0.01	0.03	
0.20	0.39	0.00	0.05	0.07	
0.27	0.41	0.03	0.00	0.03	
0.52	0.50	0.03	0.09	0.07	
0.55	0.52	0.67	0.70	0.03	
0.55	0.55	0.09	0.70	0.05	
0.55	0.30	0.71	0.71	0.02	
0.57	0.60	0.75	0.72	0.02	
0.42	0.70	0.73	0.70	0.05	
0.44	0.74	0.77	0.77	0.02	
0.40	0.77	0.79	0.78	0.01	
0.48	0.81	0.81	0.79	0.00	
0.58	1.00	0.85	0.84	0.03	
0.61	1.06	0.85	0.86	0.02	
0.65	1.14	0.88	0.87	0.02	
0.72	1.28	0.90	0.90	0.02	
0.75	1.33	0.92	0.91	0.01	0.11 D
0.77	1.38	0.94	0.92	0.00	0.20 Critical D
0.90	1.63	0.96	0.95	0.01	
1.01	1.85	0.98	0.97	0.01	D <crit.d-accept h<sub="">o</crit.d-accept>
47	n				

## Appendix C. 1. K-S test for PCA-9.

Da	ita	<b>Z</b> -scores	Cum.Freq.	f(z)	d		
-1.	58	-2.62	0.02	0.00	0.00		
-0.	96	-1.48	0.05	0.07	0.05		
-0.	94	-1.45	0.07	0.07	0.02		
-0.	64	-0.90	0.10	0.18	0.11		
-0.	64	-0.89	0.12	0.19	0.09		
-0.	.63	-0.88	0.15	0.19	0.07		
-0.	.63	-0.87	0.17	0.19	0.04		
-0.	.63	-0.87	0.20	0.19	0.02		
-0.	61	-0.84	0.22	0.20	0.01		
-0.	55	-0.73	0.24	0.23	0.01		
-0.	54	-0.71	0.27	0.24	0.00		
-0.	53	-0.70	0.29	0.24	0.03		
-0.	49	-0.61	0.32	0.27	0.02		
-0.	44	-0.53	0.34	0.30	0.02		
-0.	44	-0.52	0.37	0.30	0.04		
-0.	40	-0.45	0.39	0.33	0.04		
-0.	31	-0.29	0.41	0.39	0.00		
-0.	24	-0.16	0.44	0.44	0.02		
-0.	22	-0.11	0.46	0.45	0.02		
-0.	21	-0.10	0.49	0.46	0.00		
-0.	19	-0.06	0.51	0.48	0.01		
-0.	16	-0.02	0.54	0.49	0.02		
-0.	14	0.03	0.56	0.51	0.02		
-0.	11	0.07	0.59	0.53	0.03		
-0.	.06	0.18	0.61	0.57	0.01		
0.0	06	0.39	0.63	0.65	0.04		
0.	12	0.51	0.66	0.69	0.06		
0.	15	0.56	0.68	0.71	0.06		
0.	17	0.60	0.71	0.73	0.04		
0.	18	0.61	0.73	0.73	0.02		
0.2	23	0.70	0.76	0.76	0.03		
0.2	24	0.73	0.78	0.77	0.01		
0.4	40	1.02	0.80	0.85	0.06		
0.4	42	1.05	0.83	0.85	0.05		
0.4	49	1.18	0.85	0.88	0.05		
0.4	49	1.19	0.88	0.88	0.03		
0.:	54	1.28	0.90	0.90	0.02	0.11	D
0.	70	1.57	0.93	0.94	0.04	0.21	Critical D
0.	73	1.62	0.95	0.95	0.02		
1.	20	2.49	0.98	0.99	0.04	D <crit< td=""><td>t.D-accept <math>H_o</math></td></crit<>	t.D-accept $H_o$
4	0	n					

106

# Appendix C. 1. K-S test for PCA-10.

Data	Z-scores	Cum.Freq.	<b>f</b> ( <b>z</b> )	d		
-1.33	-2.81	0.03	0.00	0.00		
-0.60	-1.69	0.05	0.05	0.02		
-0.47	-1.50	0.08	0.07	0.02		
-0.20	-1.08	0.10	0.14	0.07		
-0.20	-1.08	0.13	0.14	0.04		
-0.15	-1.00	0.15	0.16	0.03		
-0.12	-0.95	0.18	0.17	0.02		
-0.07	-0.87	0.20	0.19	0.02		
-0.01	-0.79	0.23	0.21	0.01		
0.03	-0.72	0.25	0.24	0.01		
0.06	-0.68	0.28	0.25	0.00		
0.14	-0.56	0.30	0.29	0.01		
0.27	-0.37	0.33	0.36	0.06		
0.31	-0.30	0.35	0.38	0.06		
0.33	-0.26	0.38	0.40	0.05		
0.34	-0.25	0.40	0.40	0.03		
0.37	-0.20	0.43	0.42	0.02		
0.41	-0.14	0.45	0.44	0.02		
0.45	-0.08	0.48	0.47	0.02		
0.49	-0.03	0.50	0.49	0.01		
0.51	0.00	0.53	0.50	0.00		
0.65	0.21	0.55	0.59	0.06		
0.69	0.27	0.58	0.61	0.06		
0.69	0.28	0.60	0.61	0.04		
0.71	0.31	0.63	0.62	0.02		
0.73	0.34	0.65	0.63	0.01		
0.78	0.42	0.68	0.66	0.01		
0.86	0.54	0.70	0.70	0.03		
0.87	0.55	0.73	0.71	0.01		
1.06	0.84	0.75	0.80	0.08		
1.10	0.91	0.78	0.82	0.07		
1.18	1.04	0.80	0.85	0.07		
1.24	1.12	0.83	0.87	0.07		
1.25	1.13	0.85	0.87	0.05		
1.26	1.15	0.88	0.87	0.02		
1.36	1.30	0.90	0.90	0.03	0.08	D
1.40	1.37	0.93	0.91	0.01	0.21	Critical D
1.47	1.47	0.95	0.93	0.00		
1.86	2.07	0.98	0.98	0.03	D <crit< td=""><td>t.D-accept H<sub>o</sub></td></crit<>	t.D-accept H <sub>o</sub>
39	n					

# Appendix C. 2. F-test of the modern group vs. the archaeological group.

Modern Group		Archaeological	Group
Mean	-0.19	Mean	0.20
Standard Deviation	0.50	Standard Deviation	0.58
Sample Size $(n)$	165	Sample Size $(n)$	181

Modern & Archaeological		
F-statistic	1.36	
S <sub>1</sub>	0.58	
<b>S</b> <sub>2</sub>	0.50	
$\nu_1$	180	
$\mathbf{v}_2$	164	
α	0.05	
Critical F-statistic	1.29	
	reject H <sub>0</sub>	

### 108

t-test for unequal variances		
	Modern Group	Arch Group
Mean	-0.19	0.20
Variance	0.25	0.34
Observations	165	181
Hypothesized Mean	0	
df	343	
t Stat	-6.68	
p-value two-tail	0.0000000001	
t Critical two-tail	$\pm 1.97$	
-		reject H <sub>0</sub>

**Appendix C. 3.** T-test for unequal variance of oxygen isotope data from the modern group and the archaeological group.