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Mya arenaria and Oxygen Isotopes: An Analysis to Suggest Season of Occupation at Holmes Point East (62-6), Holmes Point West (62-8), and Joves Cove (44-13), Maine

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MYA ARENARIA AND OXYGEN ISOTOPES: AN ANALYSIS TO SUGGEST SEASON OF OCCUPATION AT HOLMES POINT EAST (62-6), HOLMES POINT WEST (62-8), AND JONES COVE (44-13), MAINE

By

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An Abstract of the Thesis Presented
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The ratio of oxygen isotopes ($\delta^{18}O$) derived from archaeological bivalves can be used to suggest whether a site was occupied seasonally or year-round. To address the question of seasonality at three archaeological shell midden sites along the coast of Maine, modern samples of the soft-shelled clam, *Mya arenaria*, were collected from tidal mudflats associated with each site once a month for one year. An average of six modern shells per month were analyzed with their resulting $\delta^{18}O$ values used to establish monthly ranges to which the archaeological samples of *Mya arenaria* were assigned; association of the archaeological shells to a monthly range provided a proxy for season of occupation at these archaeological sites. Over the course of this research, several variables that had not previously been recognized as having the potential to lead to misrepresentative results when using δ18O to analyze this species are explored, with several potential solutions suggested. These types of data are integral to our understanding of indigenous peoples' subsistence and behavior patterns along Maine's prehistoric coast, and any sources of potential error must be identified, addressed, and controlled for.

DEDICATION

This research project began from a conversation held between myself and Dr. Brian Robinson (1953-2016) in his office as we chatted about the possibility of continuing my education at UMaine by applying to the Quaternary & Climate Studies Master's Program with him as my Chair. My first two field school seasons and actual exposure to archaeology were under his direction at Holmes Point West (62-8) in 2013 and again in 2014. In 2015, I was given the opportunity to excavate by his side at the Seabrook Marsh site in New Hampshire. Everything I had learned about the art of excavation and the importance of the preservation of culture came from him, and I am forever grateful for the time I got to spend learning from and working with him. Brian was an incredible advisor, mentor, and archaeologist and while I was not able to finish my Master's research with him, he did me one last favor by asking Dr. Daniel Sandweiss to pick up where he left off. Dan has graciously and patiently helped to guide me along the rest of this journey and into my next. Thank you to you both. Brian, I hope that I have made you proud.

ACKNOWLEDGEMENTS

First, to all of my committee members, both past and present (Dr. Brian Robinson, Dr. Daniel Sandweiss, Dr. Alan Wanamaker Jr., Dr. Bonnie Newsom, Kendra Bird, and Sky Heller), thank you for being patient and for sharing your collective knowledge with me for the duration of this journey that has *finally* come to a close! I would also like to thank Dr. Alice Kelley, who has provided me with opportunities to present my research at national conferences, fostered collaborations between her work and my own, and is always willing to grab a cup of coffee and chat.

This project would not have been possible without the numerous students who have participated in the past MAPI-funded field schools at each of the three sites used in this research. Without those students, I would not have had access to thousands of excavated *Mya arenaria* chondrophores from which to select samples. A special thanks to Kendra Bird, whose knowledge of the Holmes Point sites helped to determine which units to sample, as well as finding relevant literature, and site journals. I'd like to also acknowledge Kate Pontbriand who knows firsthand the challenges of working with oxygen isotopes.

Thank you to my family, especially my parents, Elaine Blackwood and Bill Plourde, my grandparents, Dr. Raymond and Claudie Sirois, my aunt, Claire Armstrong, my future in-laws, Alan and Lisa Cyr, and my fiancé, Dom Cyr, for supporting my decision to pursue a career in Archaeology. The leg work of this research would have been a lot more tedious and lonelier without help from Dom, who accompanied me to make my modern collections once a month for one year, regardless of rain, sleet, snow, or shine, or how early or late low tide struck.

Lastly, I would like to thank the Department of Anthropology, the Climate Change Institute, and the VEMI Lab at the University of Maine, the Stable Isotope Lab at Iowa State University (Dr.

Alan Wanamaker Jr. and Suzanne Ankerstjerne), the Maine Academic Prominence Initiative (MAPI) grant, the Passamaquoddy Tribal Historic Preservation Office (Donald Soctomah), the Maine Coast Heritage Trust (Deirdre Whitehead), and the UMaine Graduate Student Government, all of whom have supported this project academically and/or financially.

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CHAPTER 1

INTRODUCTION

Archaeologists use a variety of resources to date, define, and understand the context of a site when it was in use. The types of data recovered depend heavily on the site's original purpose, its location, and the objectives of the archaeologist. In Maine, a shell midden is defined as the accumulation of discarded mollusk shell material, most frequently soft-shell clam (*Mya arenaria*) (Sanger 1979:12). These shell middens are usually located in a coastal setting where mudflats are easily accessible, exploitable sources of molluscan resources. There are approximately 2,000 registered shell midden sites along the coast of Maine with each site preserving a piece of Maine's indigenous peoples' cultural history.

The impressive preservation conditions often found at these sites are partly due to the shells themselves. The shell material of *M. arenaria* is composed of calcium carbonate (CaCO3; aragonite) and is derived from the ambient water in the coastal setting. Shells can act to neutralize the acidic sediments in Maine, helping to preserve the organic components of a site that otherwise would not have remained in the archaeological record (Sanger 1979:100-101; Hynick and Robinson 2012:1). Several types of analyses can be performed using the shells from these middens, but for the purposes of this research, *M. arenaria* shells excavated from three shell midden sites were used to infer the potential seasonality of each site based on oxygen isotope analysis. All three sites are located along the coast of Maine; two sites are located in Machiasport, and the third is located in Gouldsboro.

These three sites were selected because prior analyses have suggested a season of occupation for each location. The two sites in Machiasport, Holmes Point East (62-6) and Holmes Point West (62-8), are hypothesized to have been occupied during the summer months based on ethnographic, historical, and archaeological data. The site in Gouldsboro, Jones Cove (44-13), is hypothesized to have been occupied during the winter months based on archaeological faunal remains of fish. These two hypotheses provided an opportunity to test David Sanger's (1982) hypothesis that year-round occupation characterized both the coast of Maine and its interior.

As *M. arenaria* shells grow, they incorporate oxygen isotopes (^{18}O and ^{16}O) present within the water of their environment into their aragonitic shells. The isotopic composition of oxygen isotopes (henceforth $\delta^{18}O$; per mil) depends on seawater temperature (Epstein et al., 1953) and the isotopic composition of seawater (often linearly related to salinity; see Whitney et al., 2017). Along the coast of Maine, the ratio of these two oxygen isotopes changes throughout the year due to seasonal changes in water temperature and salinity levels. The fluctuations of these two variables are continuously recorded by the shells in the chondrophore and the ventral margin (Figure 2.3), which, when analyzed, may be used to infer when the bivalve died (the so-called season of capture). However, the bivalve must exhibit continuous growth for this method to be applicable.

In a shell midden, the death of a bivalve indicates when it was harvested. By assessing the $\delta^{18}O$ signal of the shells, the season in which the bivalve died can be inferred and used as a proxy for the site's season of occupation. This research is based upon the assumption that the coastal waters of Maine have not seen significant change over the past 5,000 years (Sanger 1996), and therefore the isotopic composition of the water has also not seen significant change. This assumption, while significant, is considered appropriate because the sites used in this research are younger than 5,000 years. To date, research in the Gulf of Maine and its coastal waters is insufficient to provide evidence against this assumption or provide a correction factor if one is detected.

For the duration of one year I collected modern samples of *M. arenaria* monthly from the tidal mudflats surrounding the three sites. Prior to each collection, the Maine Shellfish Wardens (Machiasport: Jonathan Rolfe and Gouldsboro: Mike Pinkham) were contacted for permission to access each mudflat. Acquiring modern data local to the sites under analysis, rather than using regional data, is more time intensive and costly, but provides more accurate and representative results. I used these modern collections to define seasonal parameters (each month's $\delta^{18}O$ range) with regard to the location of each site. These parameters were then used to infer the season of death for the archaeological samples excavated from Holmes Point East (62-6), Holmes Point West (62-8) and Jones Cove (44-13). The archaeological samples were selected from three collections excavated between 2006 and 2014, all housed in the Northeastern Prehistory Laboratory at the University of Maine.

The key contribution of this research resulted in identifying variables that have not been previously considered when using oxygen isotopes derived from bivalves to infer seasonality of archaeological sites. For example, growth rate is extremely varied in this species and is dependent on a multitude of influences such as location within the tidal gradient, sediment type, availability of food, predators, spawning, age, and winter shutdown periods. Without the consideration and control of these variables, the resulting $\delta^{18}O$ values and their subsequent use to infer seasonality is misrepresentative.

CHAPTER 2

BACKGROUND

The shell midden sites used in this research are primarily composed of soft-shell clams (*M. arenaria*) with 62-6 and 44-13 dating as far back as the Middle Woodland Period (2150-650 BP) and 62-8 to the Early Woodland Period (3050-2150 BP) (Robinson 2006; Bird 2017). The presence of these middens reflects the conscious decision to exploit this local resource, and the discarded shells themselves act to preserve the organic remains of the sites by neutralizing the acidity of the soil (Sanger 1979:100-101; Hynick and Robinson 2012:1). These shells can be used as proxies to determine the environmental conditions of their habitat up to their time of death by measuring the ratio of oxygen isotopes present within the shells. This type of analysis, to the author's knowledge, has not previously been performed on this species while using a complete modern shell collection as a comparative baseline for archaeological shell samples. By comparing the oxygen isotope values from the archaeological shells to those of modern shells with a known date of death, site occupation may be inferred (i.e. spring, summer, fall or winter).

2.1 Literature Review

This section is divided into three categories, 1) examples of archaeologically-driven seasonality studies of *M. arenaria* using acetate peels, 2) examples of archaeologically-driven seasonality studies of *M. arenaria* using oxygen isotopes, and 3) examples of archaeologically-driven seasonality studies of other bivalve species using oxygen isotopes. While this is not an exhaustive review of the published literature, it provides some insight into the methods currently used by archaeologists to infer seasonality. These methods guided the design of the methodologies used in this research.

2.1.1 Examples of archaeologically-driven seasonality studies of M. arenaria using acetate peels or thin sections

Several studies have used acetate peels or thin sections created from the chondrophore of *M. arenaria* shells to infer the seasonality of archaeological sites (Hancock 1982; Lightfoot et al., 1993; Ambrose et al. 2015). These studies indicate that growth lines are visible in the chondrophore and are formed tidally and annually.

Hancock (1982) collected *M. arenaria* at monthly intervals over the course of one year. These shells were used to create acetate peels to assess site seasonality. The peels indicated evidence of two growth seasons, active (March- November), and slow (December-February). Hancock also observed that growth is more rapid during the spring and summer when water temperatures are warmer and there is an increased food supply (Hancock 1982:12-13), but decreases or becomes negligible during the winter when water temperatures decrease (Hancock 1982:38). It was also noted that increased growth became apparent by February-March (Hancock 1982:38).

Lightfoot et al. (1993) selected 117 *M. arenaria* chondrophores excavated from two shell middens on Shelter Island in New York to assess site seasonality using thin sections. The authors compared the archaeological thin sections with those of a modern collection of *M. arenaria*. Using these results, the authors were able to estimate the season of death based on growth features visible at the edge of the chondrophore. However, the modern shells were collected from an area that is about 50 miles north of the sites and thus were exposed to different environmental conditions than the archaeological shells.

Ambrose et al., (2015) used 20 modern shells collected at intervals of 4–10 weeks (from June 2010 to January 2013) from an area located 13 km away from the targeted archaeological site. This irregular collection schedule does not provide the consistency needed to capture accurate seasonal cycles, and the collection area was exposed to different environmental conditions than those adjacent to the archaeological site. The authors acknowledge that the growth rate for *M. arenaria* is not linear with negligible growth in the winter months, but do not mention how to take this into account when sampling the ventral margin of shells collected during those months. Instead, they created a model for growth rate using the von Bertalanffy curve equation to estimate the expected growth of the archaeological shell's final year by dividing the observed growth by the estimated growth. That value was then used to estimate the season of death based on how much growth had taken place. The authors also make the decision to use larger archaeological shells in their analysis because they believe that growth rates and size/age relationships are unaffected by always using the largest shells (Ambrose et al., 2015:55). This, unfortunately, is a faulty assumption (see Chapter 5) because both size and age are directly affected by growth rate.

2.1.2 Examples of archaeologically-driven seasonality studies of M. arenaria using oxygen isotopes

To date, I have found only one published article incorporating the use of oxygen isotopes derived from *M. arenaria* along the east coast (Burchell et al., 2014). This study used the ratio of oxygen isotopes derived from modern samples to establish seasonal parameters that the researchers could use to infer seasonality of archaeological samples. Burchell et al., (2014) concluded that oxygen isotopic analysis is an applicable method to infer seasonality of archaeological sites. These authors used two modern *M. arenaria* shell samples collected in in the month of July from a mudflat adjacent to a known archaeological site. They took 17-23 sequential samples from the ventral margin towards the umbo, but the results indicated that one of the shells was not sampled through an entire year of growth (Burchell et al., 2014:101). They concluded that only $\delta^{18}O$ values derived from the ventral margin can be used in this type of analysis, as the $\delta^{18}O$ values derived from the chondrophore were not found to be a reliable indicator of local environmental conditions (Burchell et al 2014:101). Further work should be done to verify this conclusion due to both the small and incomplete data set, and the fact that they did not consider the local growth rate, which is extremely varied for this species (see Chapter 5).

2.1.3 Examples of archaeologically-driven seasonality studies of other bivalve species using oxygen isotopes

There have been many investigations of oxygen isotopes in molluscan species other than *M. arenaria* as proxies for the seasonality of an archaeological site (Killingley 1981; Godfrey 1988; Kennett and Voorhies 1996; Koerper and Killingley 1998; Cannon and Burchell 2017; Burchell et al. 2018) with Shackleton (1973) being the first to indicate the applicability of this method. Killingley (1981) used 14 archaeological shells consisting of four species - California mussel (*Mytilus californianus)*, owl limpet (*Lottia gigantea)*, dogwinkle (*Thais emarginata)*, black abalone (*Haliotis cracherodii)* - to determine the seasonality of a site located in Baja California, Mexico. The author compared their $\delta^{18}O$ values against known water temperature profiles from locations 70 km north of the site and 35 km south of the site. The author does not mention if the growth rates for these species are similar or consistent to make such comparisons, or if they would have an effect on the oxygen isotopic composition.

Godfrey (1988) used 192 samples derived from modern pipi mollusks (*Donax deltoides*) and 10 archaeological pipi shells. The author noticed that some of the $\delta^{18}O$ values derived from modern shells collected during January, February, and March deviated from the monthly means. To explore this phenomenon, the author compared the size of the shell to the derived oxygen isotopic value to determine at which length they began to deviate from the average monthly mean, and took them out of the dataset to reduce the scatter.

Kennett and Voorhies (1996) used 50 modern and 140 archaeological samples of the marsh clam (*Polymesoda radiata*) from the Acapetahua Estuary located in southwestern Mexico. The 50 modern shells were collected over the course of one year with five shells collected per month for ten months (June and July were excluded). The authors used oxygen isotopes to determine the difference between wet and dry seasons, but do not mention how this species' growth rate may affect their isotopic composition.

Koerper and Killingley (1998) compared oxygen isotope ratios derived from 14 California mussel (*Mytilus californianus*) and two Pacific littleneck clam (*Protothaca staminea*) archaeological specimens against known ocean oxygen isotopic values. The authors mention that growth rate for this species varies with age but not how to control for it.

Cannon and Burchell (2017) used three modern butter clam mollusks (*Saxidomus gigantea*) to determine the seasonality of 139 butter clam shells excavated from nine archaeological sites (7-28 shells per site) along the central coast of British Columbia. They did this by sequentially sampling from the ventral margin towards the umbo with 6-57 samples per archaeological shell and 4-44 per modern shell. Applying $\delta^{18}O$ values derived from three modern shells to 139 archaeological shells (regardless of sequential sampling) is an ineffective method especially when each of those nine sites is exposed to different environmental conditions. Further, while the authors acknowledge that growth rate is affected by salinity and temperature levels, they do not account for these variables in their analysis.

Burchell et al., (2018) used two modern mussels (*Mytilus sp.*) and thirteen archaeological mussel shells (*Mytilus sp.*) to determine seasonality of an archaeological site. The authors used modified methodologies when sampling slow-growing portions of the shell in an attempt to capture accurate data, but they do not mention the variables that factor into growth rate discrepancies associated with these species or how to control for them. They also use very small datasets, both archaeological and modern, to draw huge seasonality conclusions.

Such studies consistently justify the use of small sample sets (either modern or archaeological) to *accurately determine* the seasonality of a site, however their reasoning is based not on the demonstrated accuracy of such samples, but on the associated costs. This common mentality encourages research to be conducted using small sample sets regardless of the inherent errors with which they are associated. To prove the accuracy, or even use, of this method, associated costs should be planned for, and not used to justify small samples.

2.2 Holmes Point (62-6 and 62-8)

Part of my research focused on determining season of occupation for two coastal shell midden sites located in Machiasport, Maine. There have been various analyses performed at these sites, but this is the first attempt to establish seasonality using oxygen isotopes derived from archaeological *M. arenaria.* Both sites are situated adjacent to the extensive tidal mudflats of Machias Bay and on the ancestral lands of the Passamaquoddy Tribe. Holmes Point East (62-6) is located on land purchased by the Maine Coast Heritage Trust (MCHT), overseen by Regional Land Steward Deirdre Whitehead. Deirdre has been instrumental in overseeing the protection of this site (and the other cultural areas located on MCHT lands in the area) and helping to foster relationships and dissemination of information between the public and members of the Passamaquoddy Tribe about the importance of these archaeological sites.

Holmes Point West (62-8) is located on private property owned by the Brack family, who have been supportive and enthusiastic about the protection of the petroglyphs and ongoing excavation of the site. They continue to work in conjunction with the University of Maine, Donald Soctomah (Tribal Historic Preservation Officer (THPO) of the Passamaquoddy Tribe), and the MCHT in a collaborative effort both to protect and to understand the cultural contexts these sites represent.

The majority of the analyses conducted at each site have been directed towards site use and the hypothesized relationship with the Birch Point site (62-1) located across the Bay (Figure 2.1). Birch Point represents the largest known collection of petroglyphs (images that have been pecked into the surface of bedrock using a harder stone type) on the east coast of the United States and is located on Passamaquoddy land. Similar but smaller collections of petroglyphs are located throughout Machias Bay; they include anthropomorphic and animal figures as well as several images of ships (Birch Point and Salt Island) and a Christian-style cross (Birch Point). One particular collection of petroglyphs resides on a bedrock outcrop located between the 62-6 and 62-8 sites (Figure 2.1), suggesting a relationship between the petroglyphs and the shell middens. Archaeologist Mark Hedden has authored numerous publications on the Machias Bay petroglyphs, and he believes that at Birch Point, the oldest images are the farthest from the shore and their inward movement of production approximately follows the gradual oceanic inundation of their location over time (Hedden 1988:7). The proximity of Birch Point to the Holmes Point sites, along with representative faunal data in the form of site-specific selection of gray seal (*Halichoerus gryphus*) and harbor seal (*Phoca vitulina*) bullae and sea mink (*Neovison macrodon*) mandibles/maxillae, has led to the hypothesis of some form of ritualistic activity at the sites (Robinson and Heller 2017). To further this hypothesis, historic evidence suggestive of a late summer occupation for the sites is stated in George W. Drisko's book *Narrative of the Town of Machias: The Old and the New the Early and the Late*. Bird (2017:10-11) cites a passage from Drisko (1904) illustrating use of the area by Indigenous peoples:

> "In his 1904 book *Narrative of the Town of Machias: The Old and the New the Early and the Late*, George W. Drisko writes of oral records from the time of early European settlement in the area that depict "tribes of [indigenous people], who came in September of every year, from the East as far as St. John [New Brunswick] and from the West as far as Penobscot, to associate in war dances and campfires" (Drisko 1904:7). He also relates an anecdote from a Charles Gates of

> Machiasport, whose mother had told him that in her youth (the late 18th century), she "counted over one hundred birch canoes drawn up on the beach and shore opposite Machiasport, while the Indians were in Camp Fires, phullabaloos and dances, in the forest growth and wood-lands on the East side and toward Holmes Bay" (Drisko 1904:7)".

Taken together, along with the current analyses and ongoing excavations, the data thus far tend to support this hypothesis. Adding seasonality data derived from shell samples excavated from the middens themselves will enhance the current dataset and suggest a season of occupation for the two sites. These data will also contribute evidence to evaluate Sanger's (1982) hypothesis of continuous year-round occupations of the coast and the interior.

Figure 2.1: Location of 62-6, 62-8, and 62-1 sites in the context of the coast of Maine and within Machias Bay. The red star indicates the area within the mudflat where modern shells were collected, and the white star indicates the approximate location of the petroglyph assemblage located between 62-6 and 62-8.

2.2.1 Holmes Point East (62-6)

This section includes a brief synopsis of the excavations and accompanying research that has been conducted at this site, for a more in-depth analysis see Bird (2017).

2.2.1.1 Excavations

This coastal shell midden was originally excavated as part of the 1973 DownEast Survey conducted by the University of Maine and was further excavated from 2008-2010 by Dr. Brian S. Robinson (1953-2016) of the University of Maine. Dr. Robinson's research was funded through the Maine Academic Prominence Initiative (MAPI) grant in support of coastal archaeology field schools. During the 2008-2010 excavations, ¼ inch screens were used in the field, but shell samples were not collected during excavation. Two column samples were extracted and brought back to the Northeastern Prehistoric Laboratory at the University of Maine for further processing.

2.2.1.2 Data and analyses

Approximately 23 m^2 were excavated during the 1973 excavations producing artifacts associated with the Middle Woodland through Contact Periods (Bird 2017:19-20). During the 2008 excavations, a gravel house floor was recognized and subsequently analyzed (Bird 2017:20-21; Hynick and Robinson 2012).

2.2.1.3 Current analyses

62-6 is separated from 62-8 by 300 meters and a small collection of petroglyphs (Figure 2.1). While most excavation has taken place at 62-8, 62-6 was included to this seasonality research due to the two sites' close proximity and availability of data. While shells were not collected during either the 1973 or 2008-2010 excavations at 62-6, two column samples were extracted from the site during the 2008 field season. As each individual shell can only be used once in a seasonality analysis, and due to the limited number of shells available, I decided to sample from only one column to get a preliminary understanding of the site's seasonality, and to save the second column for future research purposes.

The modern *M. arenaria* shells collected for this research were obtained from the Machias Bay mudflat surrounding the 62-6 and 62-8 sites (Figure 2.1). With the help of Dom Cyr, I collected modern *M. arenaria* mollusks from this mudflat once a month for one year from May of 2016 to April of 2017 (except October, see Section 3.1 for explanation). These modern shells, referred to henceforth as the Holmes Point Blackwood Dataset (HPBD), can be applied to both 62-6 and 62-8 because this mudflat was exploited for its resources and subjected to the same environmental conditions.

2.2.2 Holmes Point West (62-8)

This section includes a brief synopsis of the excavations and accompanying research that has been conducted at this site. As with Holmes Point East, for a more in-depth analysis see Bird (2017).

2.2.2.1 Excavations

This coastal shell midden was originally excavated by the 1973 DownEast Survey conducted by the University of Maine, with semiannual excavation continued from 2008-2014 by Robinson. Excavation resumed in 2019 under the direction of Dr. Bonnie Newsom also of the University of Maine; excavations led by Robinson and Newsom were funded through the MAPI grant. During Robinson's excavation, ¼ inch screens were used with occasional fine screening using ⅛ inch screens from units bearing features. Several column samples were obtained and brought back to the Northeastern Prehistory Laboratory at the University of Maine for processing. During the 2014 field season, special attention was focused on expanding an excavation unit where a concentration of faunal remains corresponding to the now-extinct sea mink (*N. macrodon*) were recovered. There is also evidence of site use through the Contact Period in the form of lead bullets/shot, European ballast flint, and fragments of English salt-glazed chamber pot, among other items.

2.2.2.2 Data and analyses

Several types of analyses have been performed on the site including 1) a spatial analysis of the existing data including artifact and feature distribution (Bird 2017), 2) a pollen analysis (Blackwood and Hatch 2014), 3) a faunal analysis of seal bullae (Ingraham 2011), and 4) micromorphology (Andrew Heller unpublished). Each of the aforementioned analyses have provided evidence through various modalities (spatial layout of the site, radiocarbon dates, minimum number of individuals, plant life, erosion, and sedimentation), however, the question of when the site was occupied (year-round or seasonally) still remains.

2.2.2.3 Current analyses

In this research, I used the HPBD for seasonal analysis of this site as well. From 2008-2011, shell samples were not collected during excavation (Bird 2017:40), but it was noted that the midden consisted primarily of soft-shell clams (*M. arenaria*). Shell was collected beginning in the 2012 field season in the form of chondrophores, the tabular hinge of the bivalve (Figure 2.2), as each one represents a single individual and can be used in seasonality assessments. Archaeological samples were selected from four 1m x1m units based on proximity to features, dated material, and spatial location within the context of the site (Figure 2.3).

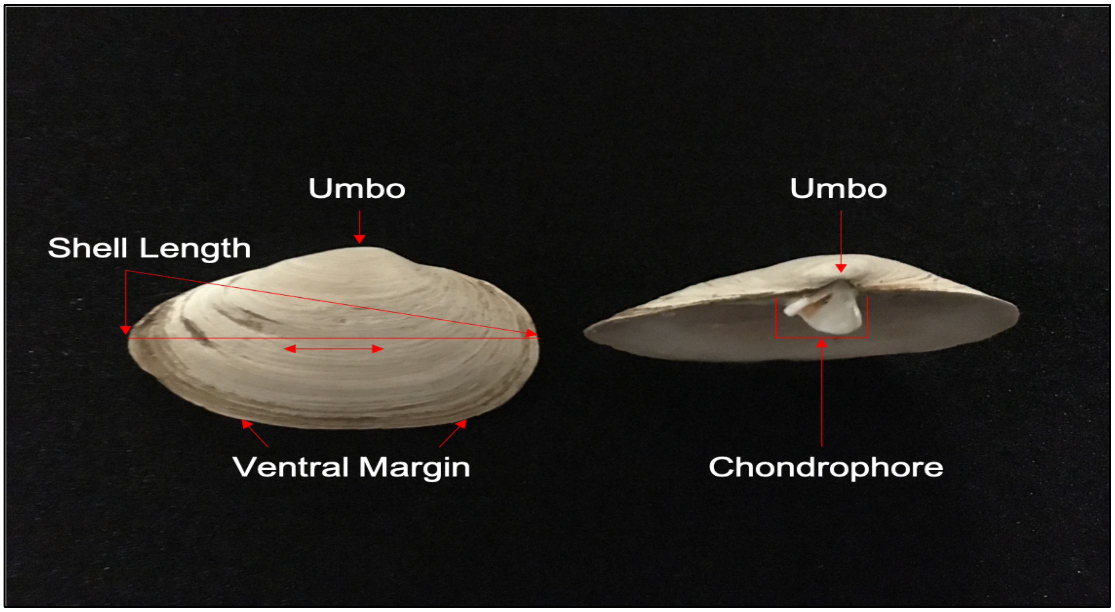

Figure 2.2. Image of a *M. arenaria* shell with labels indicating points of interest. (PC: Emily Blackwood)

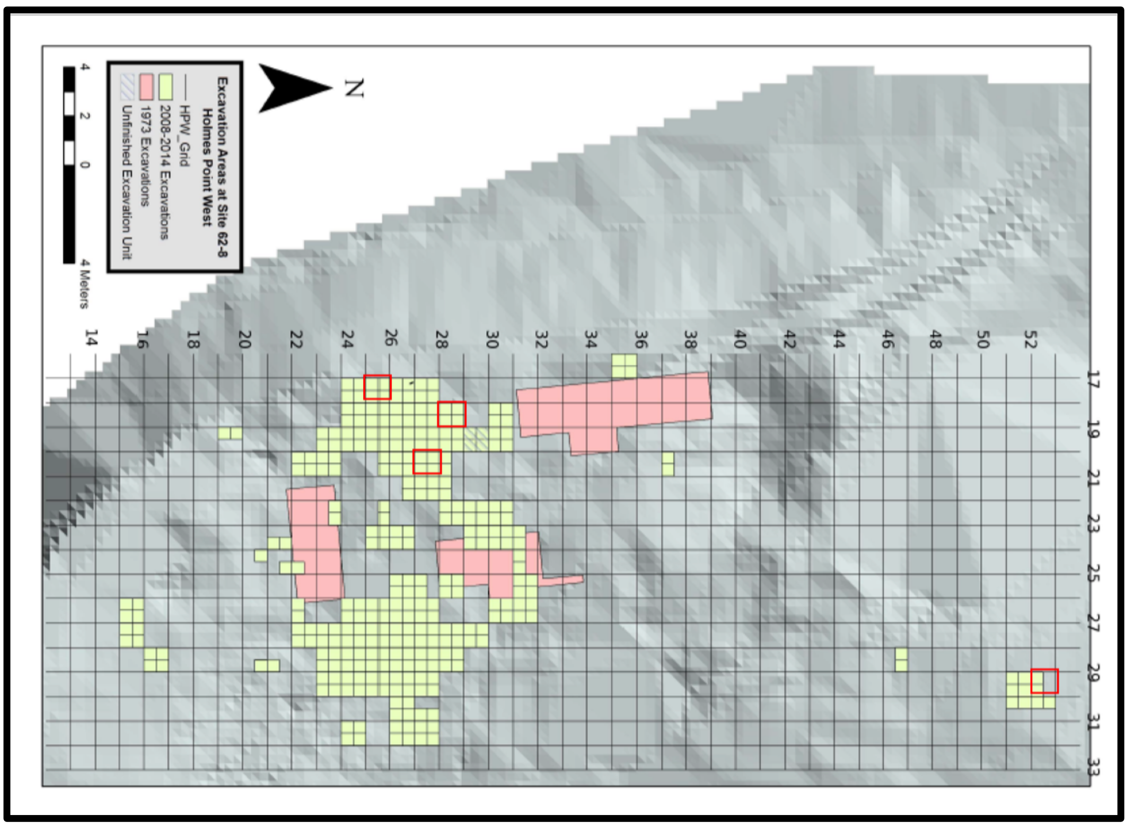

Figure 2.3. Site map of 62-8 with units used in this research outlined in red. Site map adapted with permission from: Bird, K. D. (2017). Spatial Organization and Erosion at the Holmes Point West Archaeological Site, Machiasport, Maine.

Unit 1 (N29 E19): This unit was selected because it is one of the locations from which remains of the (now-extinct) sea mink (*N. macrodon*) were recovered during excavations. Transecting Feature 28, this unit is of particular interest because only the maxilla bones of the sea mink (*N. macrodon*) have been recovered from the site, even after fine screening. Robinson developed the hypothesis that these maxillae were once part of medicine bundles, similar to those used by the Ojibwa (Robinson and Heller 2017). This hypothesis was partially tested through a pollen analysis of soil samples excavated from Feature 28 (Blackwood and Hatch 2014).

Unit 2 (N28 E21): This unit was selected because, to date, it includes the largest concentration of English salt-glazed chamber pot fragments excavated from the site. As this unit contains a large volume of historic artifacts overlaying prehistoric artifacts, determining whether the site was used in the same manner before and after European contact will add to the narrative of human behavior and site purpose.

Unit 3 (N26 E18): This unit was selected because it produced the second largest concentration (behind N29 E19) of chondrophores excavated, and is located to the west of Feature 21. This feature is regarded as one of the most important features thus far excavated on the site because it includes a hearth, a suggested lithic manufacturing area, and the lowest density of shell excavated from the site (Bird 2017:104). A micromorphological analysis performed by Andy Heller (unpublished), on a column sample excavated from the hearth revealed that the lithic debitage present within the hearth is covered by a layer of burned shell and then a layer of ash (Bird 2017:104-105).

Unit 4 (N53 E30): This unit was selected because it is a perimeter unit on the eastern side of the site. Units 1-3 are all located in the western portion of the site. Performing an oxygen isotope analysis on this unit will provide seasonality data for both sides of the site.

2.3 Jones Cove (44-13)

Jones Cove (44-13) is a coastal shell midden site in Gouldsboro, Maine situated at the northeastern most portion of Jones Cove (Figure 2.4) with a small freshwater stream entering at the head of the cove from Jones Pond (Smith 1929:3; Emily Blackwood, personal observation). Little analytical work has been done at this site due to its excavation history, but based on the presence of alewife (*Alosa pseudoharengus*) and tomcod (*Microgadus tomcod*) faunal remains Robinson (2006) hypothesized that the site was occupied during the winter months.

Figure 2.4: This figure shows the location of the Jones Cove site in the context of the coast of Maine and within Jones Cove. The red star indicates the area within the mudflat where modern shells were collected.

2.3.1 Jones Cove (44-13)

This section includes a brief synopsis of the excavations and accompanying research that has been conducted at this site.

2.3.1.1 Excavations

Originally excavated in 1928 by the Abbe Museum under the direction of Dr. Warren K. Moorehead (Smith 1929:4), the site has had a perplexing and controversial history of interpretation. Following common practice at the time, Moorehead did not screen the excavated material, used clam rakes during excavation, and opened a 100-foot-long trench near the shoreline and proceeded to excavate from the bottom up,

> "Digging was begun at the thin edge of the shells nearest the shore and gradually carried up the slope into deeper material. The numerous diggers were spaced several feet apart, and the pits they dug soon uniting formed a long trench, the dirt being shoveled behind them. Thus a perpendicular face of the shell-heap was always exposed from top to bottom. The material looked rather loose but did not crumble as it was pretty well dovetailed together. After the trench was started, digging was practically done from the bottom up -understoping, miners would term it. Small trowels and hand garden weeders were used for loosening this ancient debris, particular care being exercised where worked objects showed in the trench face. A tough, heavy sod covered the top of the shells and was broken off in chunks as it became undermined (Smith 1929:5)."

This style of excavation led to a biased representation of artifacts and site context by only recovering large intact and recognizable cultural materials, but the presence of hearths was noted, and it was observed that shell depth reached several feet below the surface (Smith 1929). Excavation continued in 2006 under the direction of Dr. Brian S. Robinson of the University of Maine funded by the MAPI grant. Prior to this excavation, the original trenches and datum were located and a new grid laid out. Although ¼ inch screens were used during the 2006 excavation, the site was quickly determined to be heavily disturbed with little to no stratigraphic context (Robinson 2006). It was also discovered that a distressing amount of small fish bone was not being recovered due to the screen size, creating a biased faunal assemblage (Robinson 2006:8) (Figure 2.5). Thus, two column samples (Figure 2.6) were collected and brought back to the Northeastern Prehistory Laboratory at the University of Maine for further processing.

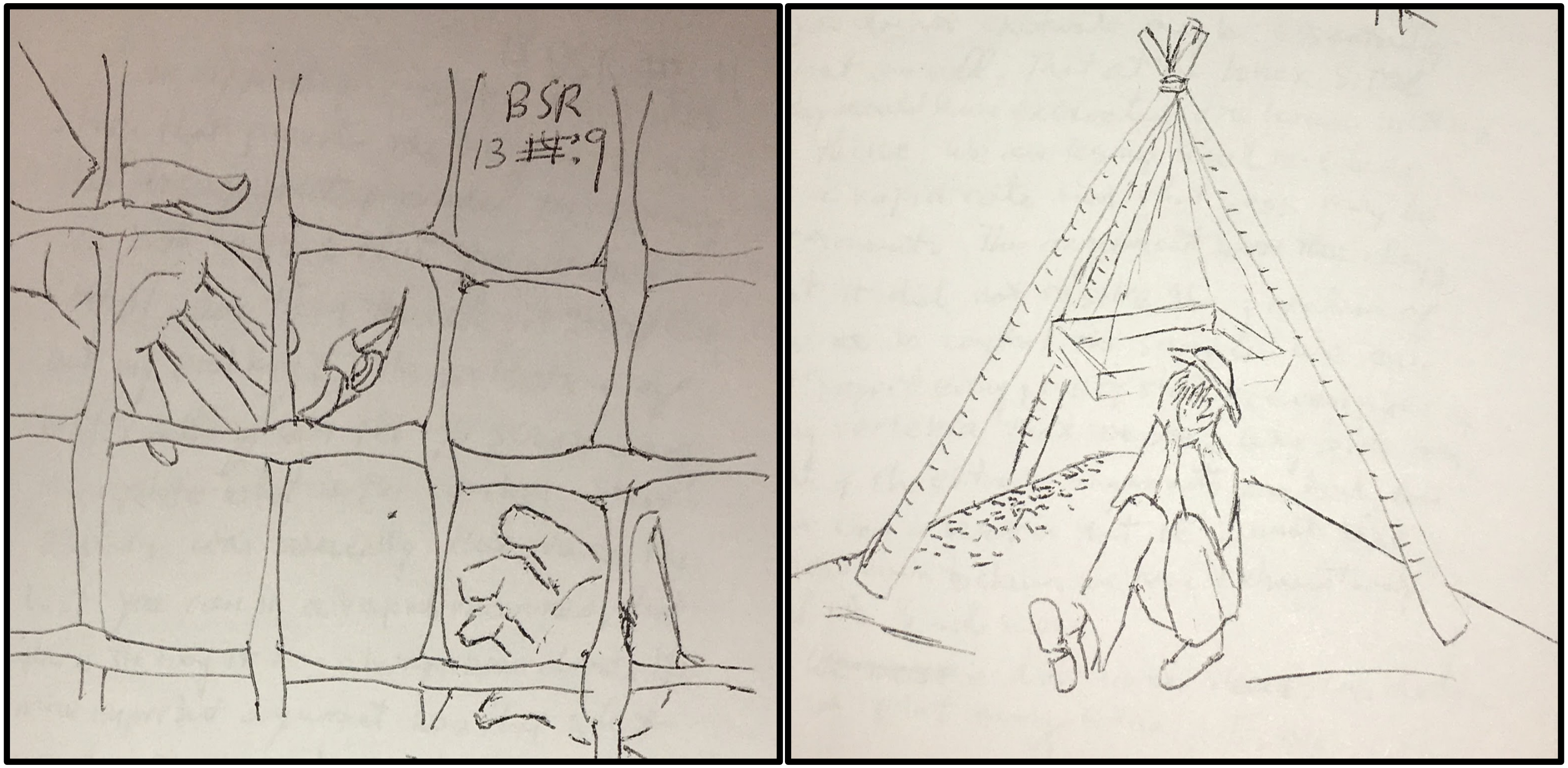

Figure 2.5: Image adapted from Robinson's 2006 field journal. A self-depiction realizing only intact fish otoliths were recovered in the ¼ inch screen, leading to the realization that an unknown amount of fractured otoliths were not being recovered.

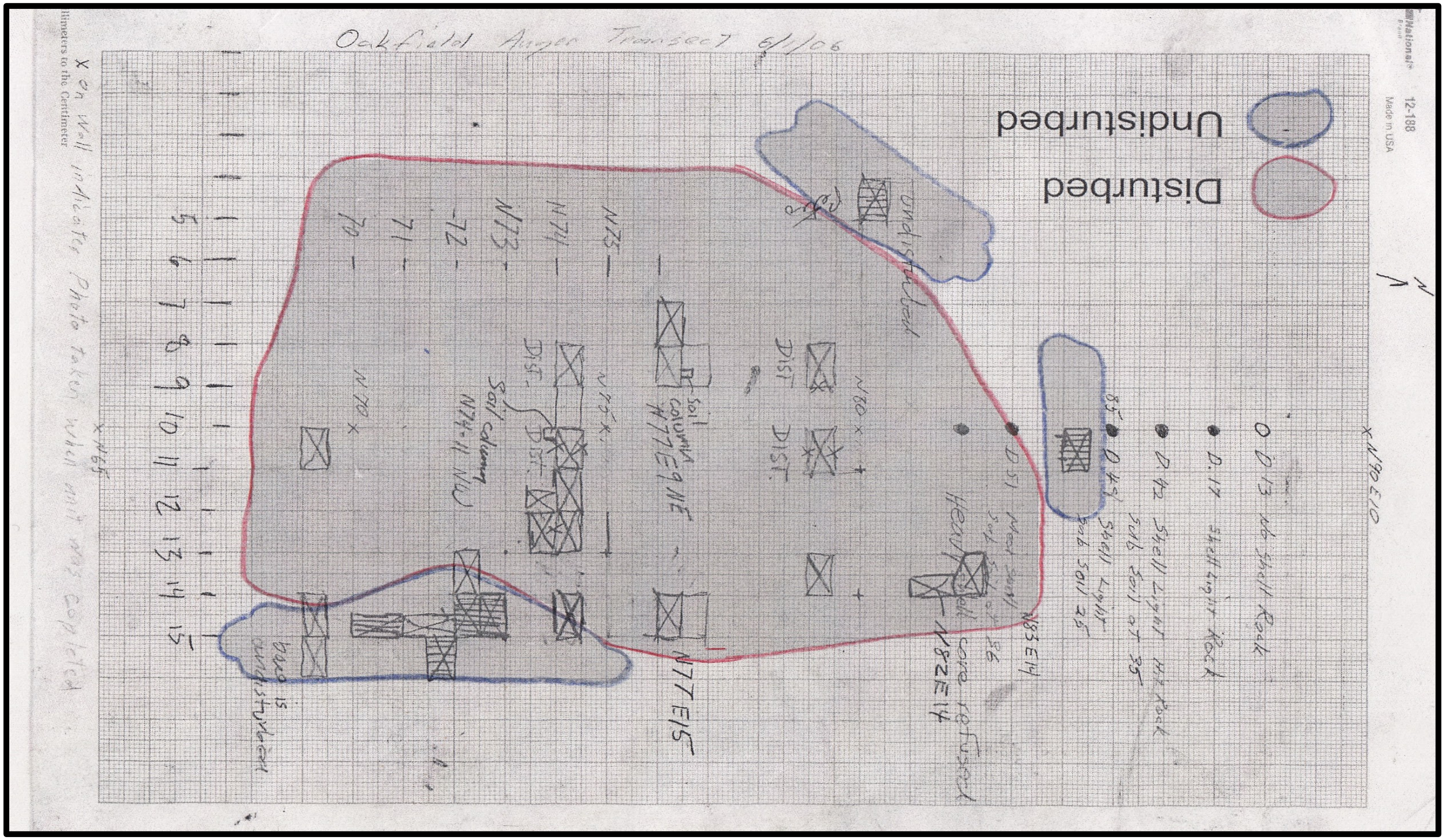

Figure 2.6. Site map of 44-13 with column samples used in this research indicated. Disturbed area is outlined in red and undisturbed areas are outlined in blue. Figure adapted from Robinson's 2006 field records.

2.3.1.2 Data and analyses

During the 1928 excavations at 44-13, 70 full projectile points were recovered representing three styles: notched base, stemmed, and triangle (Smith 1929:8). An assortment of knives, numerous scrapers, celts, whetstones, pieces of several incised stones, an array of bone tools including supposed spear points, fish hooks, darts, awls, bodkins, flakers, harpoons, one chisel, several modified teeth, and a hair comb (Smith 1929:8-22) were all recovered during the excavation; animal species present within the faunal assemblage were not individually identified. When the site was revisited in 2006, prior to recognizing the severe stratigraphic disturbance, Robinson became aware that many small fish bones were falling through the ¼ inch screens. He was particularly perplexed (Figure 2.5) at the advice bestowed upon him by a colleague to dig rapidly as that is the way it has always been done and to not worry about what falls through the screen (Robinson 2006:11). Robinson believed, and rightfully so, that this would cause a biased faunal assemblage, "what is the point...from my point of view it is the small stuff that provides the key to the site" (Robinson 2006:8-11), and he developed a screening protocol to control for this problem. Disturbance was identified by the presence of bottle caps from the 1920s at 40 cm below the surface, as well as a mixed shell matrix at all levels, shovel sized pockets of black shelless loam underlain by more shell, and sporadic patches of yellow-brown subsoil (Robinson 2006:14-15). The total area of undisturbed and disturbed sections of the site can be seen in Figure 2.6. Faunal analysis indicated the presence of alewife (*A. pseudoharengus*) and tomcod (*M. tomcod*), anadromous fish that spawn in the spring and winter respectively (Robinson 2006:8; personal communication).

2.3.1.3 Current analysis

Jones Cove (44-13) was included in this research to more accurately determine season of occupation. Due to the disturbed stratigraphy, one of the few ways to infer season of occupation is through an analysis of shells excavated from the midden. The disturbed stratigraphy does not hinder the interpretation of these data because the environmental conditions at the time of the shell's harvest are inherent in the shell itself and are not dependent on the stratigraphic level from which the shells were recovered. While the results may not be able to distinguish between occupational levels, they will be able to indicate if site use differed with regard to seasonality. Archaeological samples were selected from both column samples collected during Robinson's 2006 excavations, as no other shell was retained from the site.

The modern shells used in this research were obtained from the tidal mudflat adjacent to the site. Emily Blackwood and Dom Cyr were the primary collectors, visiting the mudflat once a month for one year from August 2016 to July of 2017 (except October, February and March, see Section 3.1 for explanation). This dataset was also concurrently used by Kate Pontbriand in her master's thesis research for the interpretation of the seasonality of the Tranquility Farm site, and it will be referred to henceforth as the Jones Cove Blackwood Dataset (JCBD).

CHAPTER 3

METHODS

To infer the seasonality of 62-6, 62-8, and 44-13, I performed an oxygen isotopic analysis on five sets of shell samples: two modern (HPBD and JCBD), and three archaeological selected from material excavated from the sites themselves using traditional oxygen isotopic analysis methods. Isotopic values derived from archaeological samples were compared to isotopic values derived from associated modern samples, and the season of occupation for each site is discussed. Several notable issues arose over the course of this research (see Chapter 5), but they do not interfere with the methodologies outlined below. Rather, the issues correspond to the bivalve species itself.

Using bivalve shells to address the issue of seasonality in archaeological shell middens is a fairly common practice (see Chapter 2, Section 1), but using a monthly modern collection across a full year as a comparative baseline is unique to this research. Over the course of one year, samples of *M. arenaria* were collected monthly at the Machias Bay and Jones Cove mudflats. This allows a more accurate representation of the bivalves' local environment to be derived and used for comparison against the archaeological samples. The ratio of oxygen isotopic values derived from the HPBD and JCBD are used to define seasonal parameters. These parameters are used to infer when the archaeological shells were harvested, and, in turn, the season(s) of occupation for each site. All shell analyses were performed at the Stable Isotope Lab (SIL) at Iowa State University under the direction of Dr. Alan D. Wanamaker Jr.

3.1 Oxygen Isotopes

The composition of *M. arenaria* shell is dependent on local water chemistry. As these bivalves grow, the calcium carbonate matrix of their shells records the ratio of oxygen isotopes (^{18}O to

^{16}O) present within the water column. This ratio is defined as $\delta^{18}O$, representing the change in the amount of ^{18}O compared to ^{16}O present within the water. The isotopic composition of oxygen isotopes depends on the seawater temperature (Epstein et al., 1953), and the isotopic composition of seawater (often linearly related to salinity; see Whitney et al., 2017). Oxygen isotopes can be used as a proxy to estimate the water temperature or salinity levels of the bivalves' local environment if a salinity-isotope mixing model (Whitney et al., 2017) has been developed. However, both seawater temperature and salinity fluctuate seasonality in coastal sites, so deconvolving this mixed signal can be difficult.

It is important to take these fluctuations into consideration when using oxygen isotopes to infer the seasonality of an archaeological site because they are correlated to seasonal fluxes of freshwater input and air temperature. These two factors have a direct impact on the ratio of the $\delta^{18}O$ recorded by the shells because freshwater has relatively low $\delta^{18}O$ values while full marine conditions have relatively high $\delta^{18}O$ values (Kennett 1996:695; Whitney et al., 2017:16). Therefore, it is crucial to account for any freshwater sources, such as streams, that would affect the seasonal isotopic composition of seawater in the mollusks' environment, highlighting the importance of acquiring local data when performing this type of analysis. In general, when salinity is controlled for, the ratio of $^{18}O/^{16}O$ is lower in shell material during warmer months because there is less fractionation of the isotopes when there is more energy in the system (Epstein et al., 1953). Shell $\delta^{18}O$ values increase in colder months due to more fractionation of the oxygen isotopes in colder temperatures (Kennett 1996:697; Koerper and Killingley 1998:77), because the separation of the isotopes is enhanced in lower energy conditions.

It has been shown that *M. arenaria* simultaneously produce two records of their local environments. The first is recorded in the chondrophore and the second is recorded by the bivalves' ventral margin (outer edge) (Figure 2.2). The chondrophore produces a much more condensed version of this record and has been used by Hancock (1982), Lightfoot et al. (1993) and Ambrose et al. (2015) to indicate season of death for this species in archaeological contexts. Lightfoot et al. (1993) also argue that the chondrophore is a more accurate representation of seasonality than the ventral margin due to the remodeling tendencies of this species' ventral margin. However, Burchell et al. (2014) argue the opposite, stating that the condensed nature of the chondrophore provides a time-averaged sample of a longer period than the shell's final month of growth and therefore, only the ventral margin provides an accurate seasonality signal. Sampling isotopes in small increments from both the chondrophore and the ventral margin of these mollusks can assess these arguments by comparing results from both parts of the same shell.

3.2 Using Oxygen Isotopes in a Seasonality Analysis

Bivalves have traditionally been analyzed using acetate peels and thin sections to reconstruct a past environment based on the life history of a shell. However, in this research, oxygen isotopes were selected to derive the season of death from archaeological shell samples based on the isotopic values measured in the ventral margin and chondrophore of modern *M. arenaria* shells. I chose this method for several reasons: 1) availability of resources and lab space to perform a seasonality analysis; 2) it is suggested to be an effective method to assess the season of death for a bivalve; and 3) it has not previously been used to infer the seasonality of an archaeological collection of shells on the basis of measurements from a 12-month, modern collection.

3.3 Mollusk Collection

This section provides an overview of how the HPBD and JCBD shell collections were created and how the archaeological shell samples were selected. Collection techniques and equipment used to obtain the HPBD and JCBD remained consistent throughout the duration of the 12-month collection interval (Figure 3.1). Selection of the archaeological shell samples varied between sites with samples from 62-6 and 44-13 obtained from column samples excavated at each respective site, and samples from 62-8 selected under the guidance of Dr. Brian S. Robinson and Kendra Bird.

Figure 3.1: Representation of how modern *M. arenaria* samples were collected. Samples were obtained using a garden hoe, rubber gloves and a cooler. This image depicts the Machias Bay mudflat.

3.3.1 Modern shell collections

With help from Dom Cyr, I visited the tidal mudflats of Machias Bay and Jones Cove once a month for one year to obtain modern samples of *M. arenaria*. These mudflats are adjacent to the sites used in this research and are assumed to be the same mudflats that were exploited by the inhabitants of the sites. In Maine, the legal minimum size of *M. arenaria* harvested recreationally or intended for sale is two inches (50.8mm). Therefore, all modern shells collected for this research have a minimum shell length (SL) of 50.8mm. Prior to each monthly collection, I called local shellfish wardens to obtain permission to access the mudflats and collect samples and to ensure that there were no prohibitory collection circumstances at the time (e.g., red tide or winter ice formation). I was unable to collect samples during the month of October for both the Machias Bay and Jones Cove mudflats due to a red tide and for the months of February and March at the Jones Cove mudflat due to winter ice formation.

3.3.1.1 Location and time of collection

Machias Bay, Maine: Two of the three archaeological sites used in this research (62-6 and 62-8) are located on the northern end of Machias Bay in Machiasport, Maine (Figure 2.1). These two sites are situated with access to the same tidal mudflat, and are assumed to have been exposed to the same environmental conditions. For these reasons, it was only necessary to create one modern collection of *M. arenaria* from this mudflat (HPBD) to define the local seasonal parameters. I made collections during low tide on the third weekend of each month from May 2016 to April 2017 (with the exception of October 2016). Refer to Figure 2.1 for location of collection within the mudflat.

Jones Cove, Maine: The third archaeological site (44-13) used in this research is located in Jones Cove in Gouldsboro, Maine (Figure 2.5). This site is situated with direct access to the tidal mudflat and located next to the mouth of Jones Pond. I made collections here during low tide on the third weekend of each month from August 2016 to July 2017 (with the exception of October 2016, February 2017 and March 2017). Refer to Figure 2.5 for location of collection within the mudflat.

3.3.1.2 Collection depth

Modern *M. arenaria* samples from the Machias Bay mudflat were consistently more frequent in number and location, at shallower depths below the surface, smaller, and more friable than those collected from the Jones Cove mudflat. On average, the *M. arenaria* collected from Machias Bay were located 4-6 inches below the surface, while *M. arenaria* collected from Jones Cove were located 7-9 inches below the surface.

3.3.1.3 Sample size

I collected between ten and fifteen modern samples monthly from each mudflat. The sample size was determined to account for breakage during transportation or shell preparation, and to ensure that a sufficient number of samples were available for current and future analyses.

3.3.2 Archaeological Shell Collections

I visually examined all archaeological shell samples for damage to the outer edge of the chondrophore and, when available, the ventral margins. As is discussed below, I found that such examinations may not reliably identify damage to the shells. I recommend that archaeological specimens considered for this type of analysis first be examined under magnification.

3.3.2.1 Holmes Point East (62-6)

Shell was not collected during excavation of the Holmes Point East site. This is common practice when excavating a shell midden due to the high volume of shell. Fortunately, two column samples were collected during excavation containing *M. arenaria* shell. I selected samples for this study from one of these two column samples (N47 W19) and cataloged them according to their depth and location. Due to the limited number of individual shells present within the column sample, I selected ten *M. arenaria* chondrophores for oxygen isotope analysis, with nine chondrophores representing levels 2-4, and one representing level 5 (Table 3.1).

Archaeological Unit	Sample Number	NW Quad	NE Quad	SE Quad	SW Quad	Level	Depth Below Datum (cm)
N47 W19	1			x		2	170-175
N47 W19	2			x		2	170-175
N47 W19	3			x		2	170-175
N47 W19	4			x		3	175-180
N47 W19	5			x		3	175-180
N47 W19	6			x		3	175-180
N47 W19	7			x		4	180-185
N47 W19	8			x		4	180-185
N47 W19	9			x		4	180-185
N47 W19	10			x		5	185-190

Table 3.1: Provenience information for site 62-6 archaeological samples.

3.3.2.2 Holmes Point West (62-8)

Protocol for collecting shell changed over the duration of Robinson's excavation at Holmes Point West site. From 2008-2010, no shell was collected, but from 2012-2014 all chondrophores and whole shells were saved throughout the site. This has resulted in a large quantity of archaeological shell samples, providing an opportunity to choose specific locations of focus for this research. I selected four key 1m x 1m units of interest (Chapter 2, section 2.2.3) for analysis with a minimum of three chondrophores selected from each level of each unit. When available, the ventral margin of whole shells recovered during excavation of these units were examined for damage and subsequently sampled if none was visible. A total of 58 chondrophores and 6 ventral margins were used in the analysis (Tables 3.2a-3.2d).

Archaeological Unit	Sample Number	Sample Location	NW Quad	NE Quad	SE Quad	SW Quad	Level	Depth Below Datum (cm)
N29 E19	13	Chondrophore		x			1x	217-225
N29 E19	14	Chondrophore		x			1x	217-225
N29 E19	15	Chondrophore		x			1x	217-225
N29 E19	16	Chondrophore		x			2x	225-230
N29 E19	17	Chondrophore		x			2x	225-230
N29 E19	18	Chondrophore		x			2x	225-230
N29 E19	19	Chondrophore		x			3	230-235
N29 E19	20	Chondrophore		x			3	230-235
N29 E19	21	Chondrophore		x			3	230-235
N29 E19	22	Chondrophore		x			4	235-237.5
N29 E19	23	Chondrophore		x			4	235-237.5
N29 E19	24	Chondrophore		x			4	235-237.5
N29 E19	25	Chondrophore		x			5	237.5-240
N29 E19	26	Chondrophore		x			5	237.5-240
N29 E19	27	Chondrophore			x		5	237.5-240
N29 E19	28	Chondrophore			x		6	240-242.5
N29 E19	29	Chondrophore			x		6	240-242.5
N29 E19	30	Chondrophore			x		6	240-242.5

Table 3.2a continued

N29 E19	31	Chondrophore			x		7a	242.5-245
N29 E19	83	Chondrophore		x			7a	242.5-245
N29 E19	84	Chondrophore		x			7a	242.5-245
N29 E19	54	Ventral Margin				x	8a	245-250
N29 E19	85	Chondrophore		x			8a	245-250
N29 E19	86	Chondrophore		x			8a	245-250
N29 E19	87	Chondrophore		x			8a	245-250

Table 3.2a. N29 E19 archaeological samples provenience information.

Archaeological Unit	Sample Number	Sample Location	NW Quad	NE Quad	SE Quad	SW Quad	Level	Depth Below Datum (cm)
N28 E21	88	Chondrophore					1x	195-200
N28 E21	89	Chondrophore					1x	195-200
N28 E21	67	Ventral Margin	x				2	200-205
N28 E21	90	Chondrophore			x		2	200-205
N28 E21	91	Chondrophore			x		2	200-205
N28 E21	92	Chondrophore			x		2	200-205
N28 E21	93	Ventral Margin			x		2	200-205
N28 E21	94	Chondrophore			x		3	205-210
N28 E21	95	Chondrophore			x		3	205-210
N28 E21	96	Chondrophore			x		3	205-210
N28 E21	97	Chondrophore			x		4	210-215
N28 E21	98	Chondrophore			x		4	210-215

Table 3.2b continued

N28 E21	64	Ventral Margin		x			4	210-215
N28 E21	65	Chondrophore		x			4	210-215
N28 E21	66	Ventral Margin		x			4	210-215
N28 E21	99	Chondrophore			x		5	215-221
N28 E21	100	Chondrophore			x		5	215-221
N28 E21	101	Ventral Margin			x		5	215-221

Table 3.2b. N28 E21 archaeological samples provenience information.

Archaeological Unit	Sample Number	Sample Location	NW Quad	NE Quad	SE Quad	SW Quad	Level	Depth Below Datum (cm)
N26 E18	55	Chondrophore			x		3	230-235
N26 E18	56	Chondrophore			x		3	230-235
N26 E18	57	Chondrophore			x		3	230-235
N26 E18	58	Chondrophore			x		4	235-240
N26 E18	59	Chondrophore			x		4	235-240
N26 E18	60	Chondrophore			x		4	235-240
N26 E18	61	Chondrophore			x		5a	240-245
N26 E18	62	Chondrophore			x		5a	240-245
N26 E18	63	Chondrophore			x		5a	240-245

Table 3.2c. N26 E18 archaeological samples provenience information.

Archaeological Unit	Sample Number	Sample Location	NW Quad	NE Quad	SE Quad	SW Quad	Level	Depth Below Datum (cm)
N53 E30	1	Chondrophore				x	3	240-245
N53 E30	2	Chondrophore				x	3	240-245
N53 E30	3	Chondrophore				x	3	240-245
N53 E30	4	Chondrophore				x	4	245-250
N53 E30	5	Chondrophore				x	4	245-250
N53 E30	6	Chondrophore				x	4	245-250
N53 E30	7	Chondrophore				x	5	250-255
N53 E30	8	Chondrophore				x	5	250-255
N53 E30	9	Chondrophore				x	5	250-255
N53 E30	10	Chondrophore				x	6	255-260
N53 E30	11	Chondrophore				x	6	255-260
N53 E30	12	Chondrophore				x	6	255-260

Table 3.2d. N53 E30 archaeological samples provenience information.

3.3.2.3 Jones Cove (44-13)

Due to the extensive disturbance at the Jones Cove site, shell was not collected in 2006, but two column samples were recovered and brought back to the University of Maine's Northeastern Prehistory Laboratory for fine screening. I selected nine chondrophore and two whole shell samples from the first column sample (N77 E9), and 15 chondrophores from the second column sample (N74 E11) with a minimum of three from each level captured within the column sample for a total of 26 samples (Table 3.3a-b).

Archaeological Unit	Sample Number	NW Quad	NE Quad	SE Quad	SW Quad	Level	Depth Below Datum (cm)
N77 E9	1		x			1	0-5
N77 E9	2		x			1	0-5
N77 E9	3		x			1	0-5
N77 E9	4		x			5	22-25
N77 E9	5		x			5	22-25
N77 E9	6		x			5	22-25
N77 E9	27		x			5	22-25
N77 E9	7		x			8	35-40
N77 E9	8		x			8	35-40
N77 E9	9		x			8	35-40
N77 E9	18		x			8	35-40

Table 3.3a. N77 E9 archaeological samples provenience information.

Archaeological Unit	Sample Number	NW Quad	NE Quad	SE Quad	SW Quad	Level	Depth Below Datum (cm)
N74 E11	28	x				1	0-5
N74 E11	29	x				1	0-5
N74 E11	30	x				1	0-5
N74 E11	31	x				1	0-5
N74 E11	32	x				1	0-5
N74 E11	33	x				1	0-5
N74 E11	34	x				5	20-25
N74 E11	35	x				5	20-25
N74 E11	36	x				5	20-25

Table 3.3b continued

N74 E11	37	x				5	20-25
N74 E11	38	x				5	20-25
N74 E11	39	x				8	35-40
N74 E11	40	x				8	35-40
N74 E11	41	x				8	35-40
N74 E11	42	x				8	35-40

Table 3.3b. N74 E11 archaeological samples provenience information.

3.4 Shell Processing

3.4.1 Sample preparation

Preparation of shell samples took place at the Stable Isotope Lab (SIL) at Iowa State University under the guidance of Dr. Alan D. Wanamaker Jr. All shells were unpacked, organized by site and level, cleaned using tap water and a soft bristled brush to remove any remaining organic material, visually assessed for quality of each shell element[1], and left to air dry. In order for a shell to be analyzed, it must meet one or more of the following criteria:

1) Intact ventral margin – no visible damage (e.g. dings, fractures, nicks, abrasions) or evidence of chemical alteration caused by diagenesis. Bivalves grow along their ventral margins, so sampling this outermost part of the shell captures the most recent environmental data. The derived $\delta^{18}O$ values from this portion of the modern shell define the seasonal parameters to which the derived $\delta^{18}O$ values from the archaeological shells are assigned.
2) Intact chondrophore – no visible damage. The chondrophore is naturally tougher than the ventral margin of the shell and captures the same environmental data, but at a

[1] This initial assessment later proved insufficient, and it was necessary to assess the ventral margins via microscope.

more condensed scale. The $\delta^{18}O$ values from this portion of the modern shells were sampled and used to crosscheck the $\delta^{18}O$ values of their corresponding ventral margin. They were also sampled because the majority of the archaeological samples available from the three middens are derived from chondrophores.

3) Interannual growth increments – no visible damage or evidence of diagenesis to the exterior of the shell. Sampling this portion of the shell remains controversial because of the difficulty in accurately identifying the origin and end for each individual year of growth. However, if properly identified, sampling this portion of the shell should provide the environmental history for a mollusk during that year's growth.

3.4.2 Sample processing

In order to obtain the necessary samples, a Dremel® 300 and 3000 rotary tool was used to remove material from each shell's determined sample location (ventral margin, chondrophore, or interannual growth increments). This process produces approximately 0.3 mg of calcium carbonate powder that is collected and transferred to a test tube to await analysis. Two different bit styles were used on the Dremel®: for the chondrophore and ventral margin samples, we used a Brasseler USA's 845.11.010 HP Medium Flat End Cylinder Diamond bit, and for the interannual samples, we used a Brasseler USA's 801.11.010 HP Medium Round Diamond bit. The samples used in this research were run in three different sample sets. We prepared the first group of shells at the SIL at Iowa State University while we prepared the other two groups at the University of Maine and mailed them to the SIL for analysis. This was partly due to time constraints and sample availability, but also partly due to mechanical issues at the SIL causing loss of data and requiring replacement samples. Below, I outline the steps used in this research.

1) Assess and select shells to be sampled.

2) Record contextual information (site name, location, unit, level, depth, collectors, date of collection) to create a shell database for each site.
3) Establish a sample identification protocol and label test tubes accordingly.
4) On the lowest speed, use the Dremel® to obtain the desired sample amount (.20-.40 mg) over a glass plate. Using a higher speed will create wind, cause oversampling, and increase the potential to sample through the calcium carbonate layer of the shell into the aragonite layer leading to contamination or damage to the structure of the shell.
5) Using a razor blade, scrape the calcium carbonate powder into the appropriately labeled test tube.
6) Clean the razor blade and the glass plate with ionized water to reduce the risk of contamination.

3.4.3 Mechanical processing

A mass spectrometer was used to measure $\delta^{18}O$ values within each shell sample. The SIL uses a Thermo Finnigan Delta Plus XL mass spectrometer attached to a GasBench II with a CombiPal autosampler; this setup produces a long-term precision of ±0.09‰ (1 standard deviation) for $\delta^{18}O$. At least one isotopic standard (NBS-18; NBS-19) was used for about every five samples. SIL Lab Manager Suzanne Ankerstjerne completed all post analysis mechanical processing of data.

3.5 Water Collection and Processing

Samples of marine water were collected from both the Machias Bay and Jones Cove mudflats over a 24-hour period from September 5-6, 2018 at Machias Bay and August 25-26, 2018 at Jones Cove. These water samples provide a baseline of the salinity and oxygen content in the water that can be used to correct the findings from oxygen isotope readings from the shells. Collecting these samples also shows the environmental conditions under which the modern samples grew.[2]

3.5.1 Field collection of water samples

The same protocol for collecting marine water was used at each mudflat. A 50 ml sterile plastic vial was used to collect a sample of water at the low tide mark on the hour for 24 hours. During collection, each vial was dunked and rinsed with marine water before being completely submerged in the water. The caps were secured underwater to ensure the purest and fullest sample. Water was collected as far away from sources of freshwater as possible to reduce the potential of misrepresentative results, as well as avoiding areas with high sedimentation. As both locations involved walking out across a large mudflat, occasional sedimentation was unavoidable, but allowing the water to settle or collecting away from disturbed sediments was generally possible. Each vial was labeled with the location, date, and hour of collection. After collection, all samples were then placed in a cool or refrigerated environment to prevent evaporation.

3.5.2 Laboratory preparation of water samples

To prepare the water samples, an Eppendorf pipette with adjustable volume 500-2500Vl was used to siphon approximately 2 ml of water into a 2 ml vial. This process was repeated for a total of 52 water samples (twenty-four from each mudflat, one from a ponded area that feeds into the Machias Bay mudflat, one from a separate location at Machias Bay where modern collection took place for several months due to closure of one area of the flat, one from a freshwater stream

[2] Although water samples were not collected when shells were collected, the author suggests collecting water samples concurrently with the modern shell collection in order to understand the relation of fluctuating salinity levels and water temperature throughout the year to isotopes incorporated in the shells.

feeding into Jones Cove from Jones Pond, and one from the low tide mark at Jones Cove during the final modern collection).

3.5.3 Water sample processing

Water samples were tested with a Picarro L2130-i Isotopic Liquid Water Analyzer with autosampler and ChemCorrect software. Each sample was measured six times with only the last three injections used to calculate the mean isotopic values to account for memory effects. For every five samples, at least one reference sample (VSMOW2, USGS 48, USGS 47) was used to assign the data to an appropriate isotopic scale and for regression-based isotopic correction. An average precision better than ±0.20‰ (1 standard deviation) was common for $\delta^{18}O$. Each water sample was also tested for its salinity levels using a Vernier LabQuest ll with a chloride sensor.

CHAPTER 4

RESULTS

This section presents the results of the oxygen isotopic analysis performed on 62-6, 62-8, and 44-13. While this is not an exhaustive seasonal analysis of these archaeological sites, these data do provide some interesting results. Once all shell samples (modern and archaeological) had been run, it became apparent that several months from both the HPBD and JCBD contained significant noise in the form of large variations of $\delta^{18}O$ values. Additionally, I identified several shells that had been sampled a second time due to an error made by Kate Pontbriand during the sampling that took place at the University of Maine. I attempted to correct for this by sending in additional samples from previously unsampled shells in order to create the large dataset necessary for this type of analysis. However, the returned $\delta^{18}O$ values from these samples did not reduce the noise within the datasets. While some noise is expected due to the natural variation of growth rates between shells of the same age, I believed the spread was too large. Upon further research, I discovered that the growth rate for *M. arenaria* is not only affected by the water chemistry of its environment, but by numerous additional factors such as the location of the bivalve within the tidal gradient, sediment type (both grain size and composition), water temperature, food availability, predators, age, the onset of spawning, and exposure to winter shutdown periods (Dow and Wallace 1957; Commito 1982; Newell 1982; Newell and Hindu 1982; Beal et al. 2001).

The literature review (Chapter 2, section 2.1) indicated that the issue of growth rate is acknowledged by the archaeological community investing in seasonality studies, but it has yet to be addressed as a serious issue. As *M. arenaria* age, the amount of shell they deposit yearly decreases, thus increasing the potential to oversample (i.e., integrate more time than desired) and obtain $\delta^{18}O$ results that capture several months of data as opposed to isolating the final month. Research conducted by Dow and Wallace (1951) indicated that it takes *M. arenaria* from Eastport, Maine to Cutler, Maine (Machias Bay is located within this range) an average of 5 years to reach the legal size of 50.8mm and grow at a fairly consistent rate. The growth rate in this area begins to decrease after age 6 with an average SL (shell length) of 58.95mm. However, they also indicate that the growth rate for *M. arenaria* near Sullivan, Maine is slower than this average, taking an average of 10 years to reach legal size as opposed to 5 years.

Due to these varying growth rates, I chose to exclude shells from the HPBD and JCBD that measured over 58.95mm SL from the analysis. Each modern shell was carefully measured (to the nearest mm), and then examined under a 10x magnification to determine if too much of the ventral margin had been sampled by comparing the sampled portion (visible under magnification) to the rest of the ventral margin. Measurements were taken using a General ULTRATECH carbon fiber composite digital caliper, but as the shells were not measured prior to sampling, the values provided in this chapter are considered to reflect the minimum total SL for each set of shells. This is reminiscent of the research conducted by Godfrey (1988) where $\delta^{18}O$ values derived from shells were removed from the dataset if they were over a certain length to reduce the scatter of $\delta^{18}O$ values. I found that 43 of the 74 HPBD shells and 51 of the 60 JCBD shells were too large (and therefore too old), had damage to the ventral margin, or were oversampled and could not be included in this analysis as they would likely provide misrepresentative data. Further, Beal et al. (2001:138) found that 95% of the growth for *M. arenaria* is completed between February and September with 99% by early December, suggesting that the $\delta^{18}O$ samples taken from shells collected in the winter months are providing $\delta^{18}O$ values more likely to be reflective of earlier months when the shells stopped growing.

4.1 Machias Bay, Maine

I sampled between five and eight modern shells from each month for a total of 74 samples (Appendix A); however, only 31 were found to be both undamaged and measure less than 58.95 mm SL (Table 4.1a). They are ordered from the first month of collection (May 2016) to the final month (April 2017). Each pair of shells was assigned a unique identifier to link the sample to a specific set number within each month of the HPBD; the occurrence of several sets of identifiers represent the multiple phases of samples taken during this research. Ultimately, of those 31, only 14 were used due to the winter shutdown period and weather events that may have influenced results (Tables 4.1b). Consequently, all months are too underrepresented within this now-incomplete dataset to infer anything beyond a tentative seasonal assessment for both the 62-6 and 62-8 sites. Traditional use of oxygen isotopic methods have not considered growth rate to play a crucial role in the derived $\delta^{18}O$ values for this species, and have not accounted for the winter shutdown period where negligible growth transpires. When this is not factored into the analysis, the results mimic a typical sine curve that demonstrates seasonal fluctuations and is interpreted as such by Burchell et al. 2014.

Sample Identifier	$\delta^{18}O$ Value	Modern Month	Sample Location	Set Number	Shell Length (mm)	Chondrophore Length (mm)
HP_160001	0.89493	May-16	Ventral Margin	1	46.7	8.23
HP_160019	1.46427	May-16	Ventral Margin	3	48.6	8.01
HP_0089	1.2073	May-16	Ventral Margin	7	57.62	8.19

Table 4.1a continued

HP_160030	1.27334	Jun-16	Ventral Margin	1	54.27	umbo broken
HP_0075	1.8299	Jun-16	Ventral Margin	2	57.88	9
HP_0079	1.5034	Jul-16	Ventral Margin	12	53.72	umbo broken
HP_0083	0.4134	Aug-16	Ventral Margin	2	54.59	6.66
HP_160053	0.12724	Sep-16	Ventral Margin	3	56.46	umbo broken
HP_160056	0.22173	Sep-16	Ventral Margin	7	57.74	8.17
HP_160088	1.18196	Nov-16	Ventral Margin	11	50.74	8.37
HP_0022	1.1121	Nov-16	Ventral Margin	19	54.04	8.71
HP_0024	0.8975	Nov-16	Ventral Margin	17	55.06	8.22
HP_0005	0.7764	Nov-16	Ventral Margin	18	57.49	8.79
HP_160100	1.42113	Dec-16	Ventral Margin	2	56.74	8.75
HP_0028	0.9392	Dec-16	Ventral Margin	3	52.94	7.73
HP_0032	0.7935	Dec-16	Ventral Margin	5	48.23	7.2
HP_170103	1.56537	Jan-17	Ventral Margin	2	55.51	8.81
HP_170113	0.82309	Jan-17	Ventral Margin	8	44.49	6.88
HP_170114	1.48085	Jan-17	Ventral Margin	9	48.13	7.58
HP_0034	1.5777	Jan-17	Ventral Margin	15	51.22	7.79
HP_0036	1.1146	Jan-17	Ventral Margin	6	49.2	umbo broken

Table 4.1a continued

HP_0038	1.5855	Jan-17	Ventral Margin	16	55.69	8.88
HP_0007	1.9320	Jan-17	Ventral Margin	11	57.55	9.61
HP_170115	0.41249	Feb-17	Ventral Margin	9	56.81	8.73
HP_170126	0.45836	Feb-17	Ventral Margin	10	44.88	umbo broken
HP_0045	0.6223	Feb-17	Ventral Margin	12	46.56	umbo broken
HP_170127	0.92592	Mar-17	Ventral Margin	6	49.64	7.39
HP_0051	0.9381	Mar-17	Ventral Margin	10	47.96	6.69
HP_0010	0.8082	Mar-17	Ventral Margin	12	44.7	7.47
HP_0055	1.9262	Apr-17	Ventral Margin	6	41.38	7.37
HP_0057	1.2811	Apr-17	Ventral Margin	5	46.91	7.52

Table 4.1a. HPBD $\delta^{18}O$ values of *M. arenaria* shells measuring less than 58.95 mm SL.

Sample Identifier	$\delta^{18}O$ Value	Modern Month	Sample Location	Set Number	Shell Length (mm)	Chondrophore Length (mm)
HP_160001	0.89493	May-16	Ventral Margin	1	46.7	8.23
HP_160019	1.46427	May-16	Ventral Margin	3	48.6	8.01
HP_0089	1.2073	May-16	Ventral Margin	7	57.62	8.19
HP_160030	1.27334	Jun-16	Ventral Margin	1	54.27	umbo broken
HP_0075	1.8299	Jun-16	Ventral Margin	2	57.88	9

Table 4.1b continued

HP_0079	1.5034	Jul-16	Ventral Margin	12	53.72	umbo broken
HP_0083	0.4134	Aug-16	Ventral Margin	2	54.59	6.66
HP_160053	0.12724	Sep-16	Ventral Margin	3	56.46	umbo broken
HP_160056	0.22173	Sep-16	Ventral Margin	7	57.74	8.17
HP_170127	0.92592	Mar-17	Ventral Margin	6	49.64	7.39
HP_0051	0.9381	Mar-17	Ventral Margin	10	47.96	6.69
HP_0010	0.8082	Mar-17	Ventral Margin	12	44.7	7.47
HP_0055	1.9262	Apr-17	Ventral Margin	6	41.38	7.37
HP_0057	1.2811	Apr-17	Ventral Margin	5	46.91	7.52

Table 4.1b. HPBD $\delta^{18}O$ values of *M. arenaria* shells measuring less than 58.95 mm SL, and with shells from the winter shutdown period removed.

Figure 4.1a and 4.1b represent what the HPBD used in this research looks like if the winter shutdown period and SL are ignored. Figure 4.1a indicates the average shell $\delta^{18}O$ value derived from each modern month of collection compared to water temperature derived using the modified Grossman and Ku (1986) equation: $T(°C) = 20.6 - 4.34*(\delta^{18}O_{aragonite} - (\delta^{18}O_{water} - 0.27))$ where $\delta^{18}O_{water}$ and $\delta^{18}O$ from the shell are used to derive water temperature at the time of bivalve collection (Wanamaker & Gillikin 2018).When displayed as such, the values appear to indicate seasonal fluctuations attributed to fluctuating salinity and seawater temperatures. Figure 4.1b indicates the average shell $\delta^{18}O$ value derived from each modern *M. arenaria* sampled, the $\delta^{18}O$ values from November-January overlap with $\delta^{18}O$ values derived from February-September. The variation seen within individual months has traditionally been justified as the natural variation within the species, however, traditionally, SL has not been considered as a contributing variable.

Figure 4.1c and 4.1d represent the data when SL and the winter shutdown period are factored in. Figure 4.1c indicates the average $\delta^{18}O$ values derived from modern *M. arenaria* shells measuring less than 58.98mm SL from months associated with growth compared against the derived water temperature. A total of 14 shells were used with the months of July and August represented by only one shell each. If a trend is to be surmised based on this limited dataset, it could be suggested that August and September are associated with lower shell $\delta^{18}O$ values than the months of March-July, a finding that makes sense as that is when Maine's coastal waters are warmest and warmer water temperatures corresponds to low $\delta^{18}O$ values. Figure 4.1d indicates the $\delta^{18}O$ values derived for all modern *M. arenaria* shells measuring less than 58.98 mm SL. While the $\delta^{18}O$ values associated with shells from November-January are not included in the analysis, they are included in the figure to demonstrate that although their SL measures less than 58.98mm, their $\delta^{18}O$ values still overlap with the $\delta^{18}O$ values derived from March-July. Similarly, the $\delta^{18}O$ values associated with February are not included in the analysis, but are included in the figure to demonstrate the importance of understanding the context associated with the collection of the modern *M. arenaria* shells. The $\delta^{18}O$ values for February may be attributed to a nor-easter storm and subsequent melt 5 days prior to the shells being collected. Without knowing this context, it would appear that the month of February has lower $\delta^{18}O$ values, which are associated with warmer water, a correlation that is unlikely for Maine's coastal waters during the winter. It is also possible that the bivalves were not actively mineralizing calcium carbonate (growing) at all during this month, warranting further research.

A total of 43 from the 74 HPBD shells were automatically removed from the dataset because they measured over 58.95mm in total SL, were damaged along the ventral margin, or were oversampled. Of the remaining 31 shells, I removed an additional 14 from the sample because they were associated with the winter shutdown period (November, December, and January), and I took out three more representing the month of February due to the potential of weather-influenced events. The February shells were collected on February 18th, 2017, but from the 12th-13th a nor'easter (large winter snow storm) dropped ~38 inches of snow in this area of the coast (Birkle 2017) followed by fairly warm temperatures. As snow, which is freshwater, has lower $\delta^{18}O$ values, and because *M. arenaria* has been shown to begin growing during this month (Ambrose et. al 2015) it can be surmised these shell $\delta^{18}O$ values may reflect the nor'easter, rather than typical conditions during the month of February. This further lowers the accuracy and reduces the total number of usable modern shells to a mere 14. However, it does emphasize the importance of using local shell data, highlights the need to be aware of the environmental conditions associated with shell growth, and raises the question of whether we may be able to recognize these types of events in the archaeological shells.

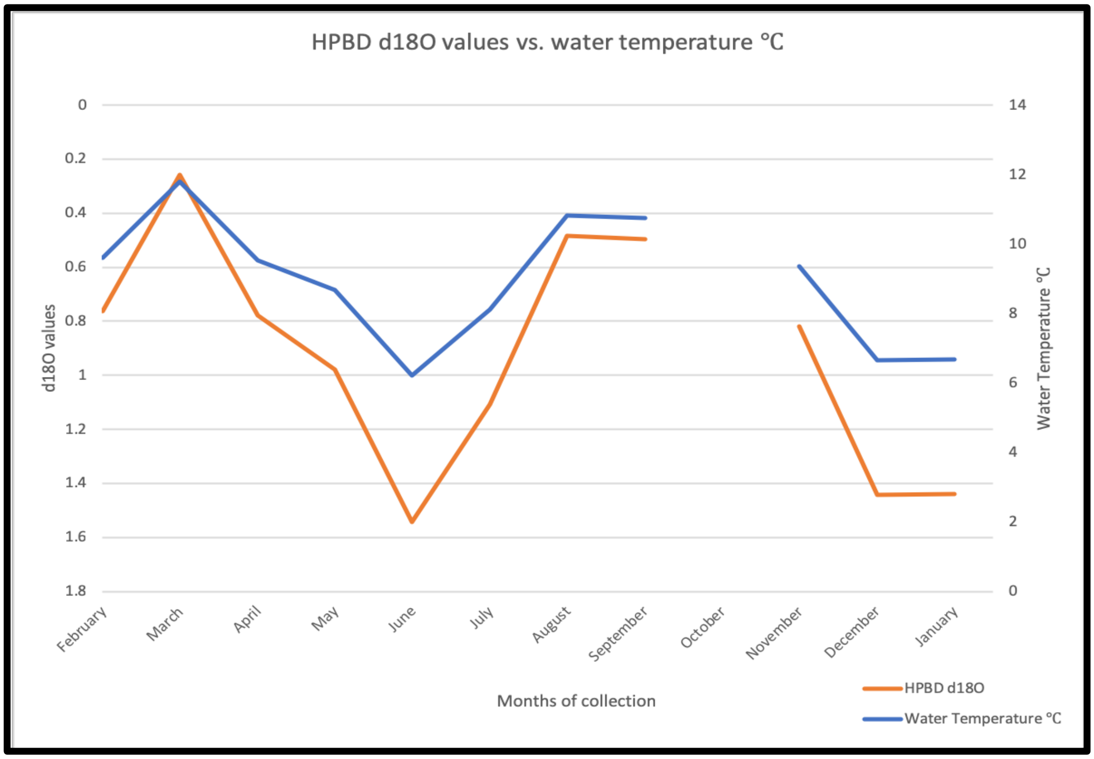

Figure 4.1a: HPBD average shell $\delta^{18}O$ value compared against derived water temperature without considering SL or the winter shutdown period. The values appear to indicate seasonal fluctuations attributed to fluctuating salinity and seawater temperatures.

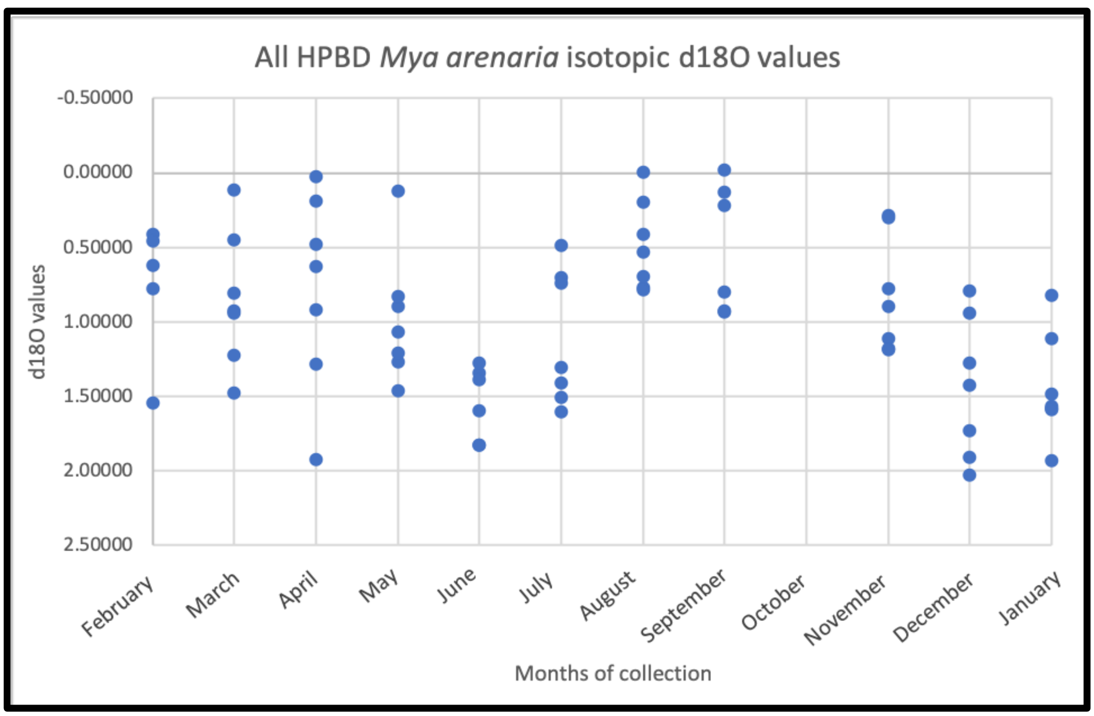

Figure 4.1b: HPBD average shell $\delta^{18}O$ values without considering SL or the winter shutdown period.

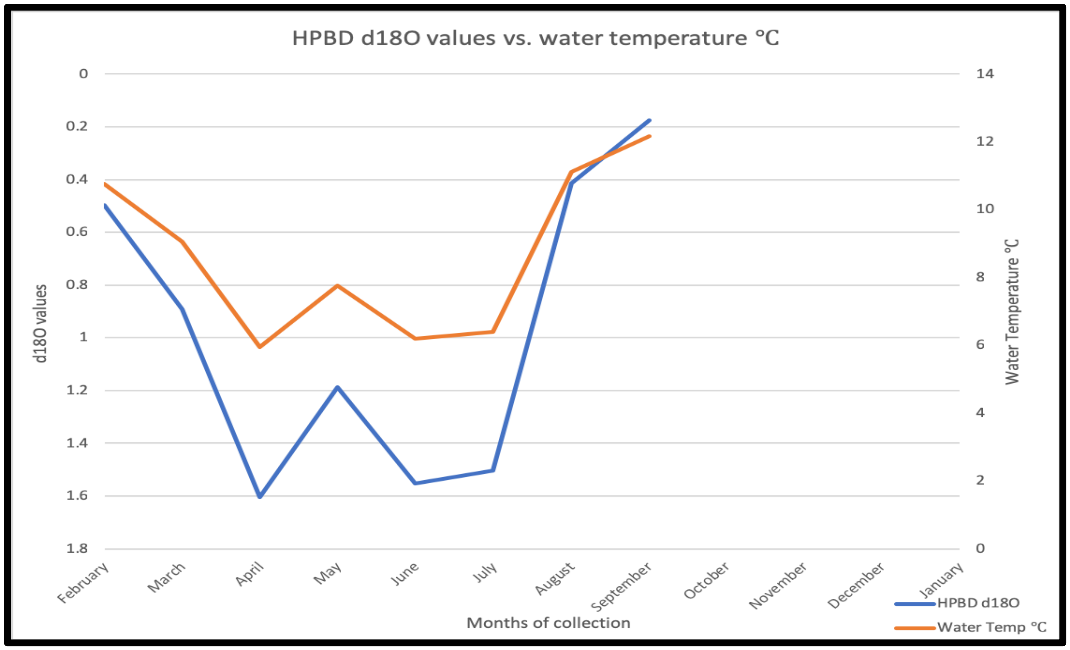

Figure 4.1c: Average HPBD $\delta^{18}O$ values derived from *M. arenaria* measuring less than 58.95mm SL and associated with months of growth compared to derived water temperature. August and September appear to be associated with lower shell $\delta^{18}O$ values than the months of March-July.

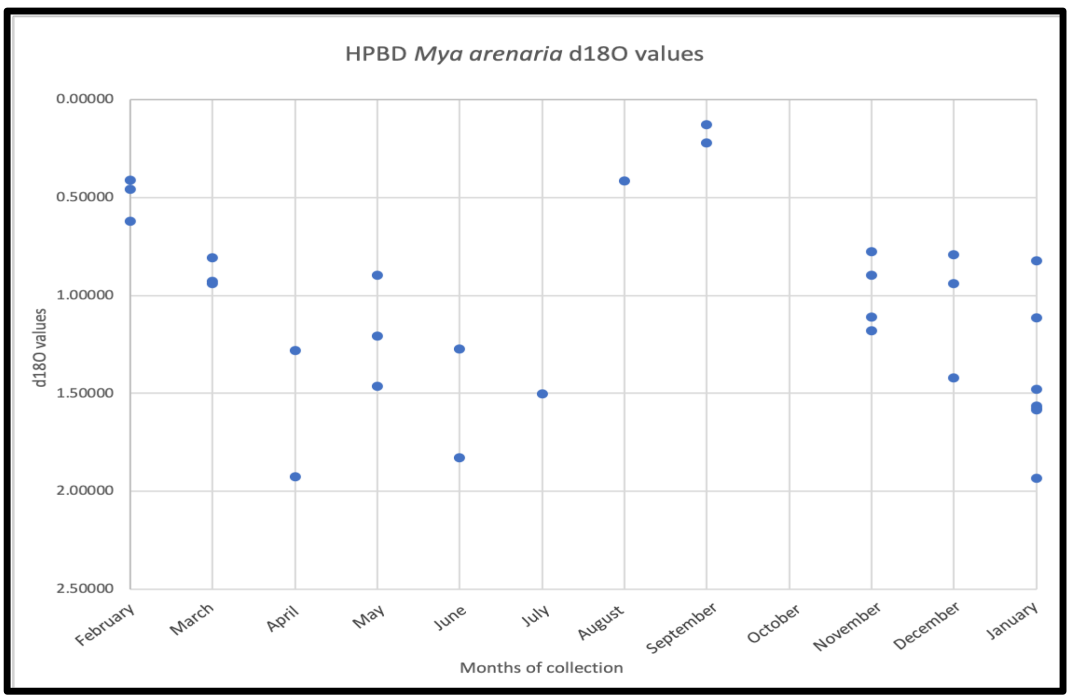

Figure 4.1d: HPBD $\delta^{18}O$ values derived from all *M. arenaria* shells measuring less than 58.95 mm SL; values from November-February are not included in the analysis (see above discussion).

4.1.1 Holmes Point East (62-6)

A total of 10 archaeological shell samples were obtained from one column sample representing four levels, equal to 20 cm of excavation depth below datum with 5 cm levels (Table 3.1). As this is a limited number of shells upon which to base the seasonality of the site, this analysis must be considered preliminary. Table 4.2 presents the results of this analysis with each modern month's minimum and maximum $\delta^{18}O$ values on the left and archaeological sample identification numbers and their associated $\delta^{18}O$ values across the top. The archaeological $\delta^{18}O$ values are then assigned to the corresponding modern $\delta^{18}O$ value range; a small 'x' indicates the archaeological $\delta^{18}O$ value falls within that month, and a small 'o' indicates it could potentially be associated with that month. Archaeological samples in red indicate that the $\delta^{18}O$ value could either not be assigned, or only potentially assigned to a modern month. The reason for this is unknown but a few reasons are suggested: 1) the modern dataset is too small, 2) human error related to sampling technique, 3) the chondrophore or ventral margin did not represent the season of death due to abrasion or breakage causing time-averaging, 4) diagenesis altered the shells' chemistry due to percolating groundwater, or 5) the water chemistry during the time these mollusks lived was different than present day conditions. I could only assign three of the archaeological samples to a definitive monthly range (September), but the other 7 could potentially be assigned to August or September. While these results are preliminary, they do indicate the same hypothesized occupation time as 62-8.

			Archaeological Samples N47 W19									
			1	2	3	4	5	6	7	8	9	10
Modern Month	**Min d18O**	**Max d18O**	0.4701	0.1652	0.4162	-0.1917	0.2819	0.0351	0.5783	0.1668	0.2091	-0.1282
May (3)	0.89493	1.2073										
June (2)	1.27334	1.8299										
July (1)	1.5034											
August (1)	0.4134		o		o				o			
September (2)	0.12724	0.22173		x		o	o	o		x	x	o
October (0)												
November (4)												
December (3)												
January (7)												
February (3)												
March (3)	0.8082	0.9381										
April (2)	1.2811	1.9262										

Table 4.2: Comparison of archaeological $\delta^{18}O$ values from 62-6 to $\delta^{18}O$ values from the HPBD. See Table 3.1 for provenience information.

4.1.2 Holmes Point West (62-8)

Initially, I prepared a total of 82 samples from archaeological shells excavated from four units across the site (see Chapter 2, section 2.2.3 for unit descriptions). Unfortunately, 55 samples were lost during the initial run. 74 new samples were prepared and analyzed for a total of 101, of which I used 63. The $\delta^{18}O$ values of six ventral margins and two chondrophores were not included in the analysis due to damage, and the $\delta^{18}O$ values measured from the interannual sequence (30 samples) are not used for comparative purposes as they pertain to an entire year's growth and not the bivalves's final month. The majority of the archaeological $\delta^{18}O$ samples were taken from chondrophores due to the lack of whole shells excavated from the site, but the ventral margin was sampled when available. The 63 samples were obtained from four excavated units of varying depths below datum with 5 cm levels (Tables 3.2a-d). Tables 4.3a-4.3d represent the four archaeological units assessed in this analysis and indicate the potential of a Summer / Fall occupation of the site; the tables are designed in the same manner as Table 4.2.

Table 4.3a represents the $\delta^{18}O$ analysis for 24 archaeological shell samples excavated from unit N29 E19; two chondrophores, six ventral margins and 23 interannual sequence samples are not included due to damage (chondrophores and ventral margins) or inapplicability (interannual sequence). 23 chondrophores and one ventral margin were selected from the northeast quad representing levels 1x-8a. The total depth below datum was 33 cm: level 1x had a depth 8 cm below datum, levels 2x, 3 and 8a were 5 cm levels, and levels 4-7a were 2.5 cm levels (Appendix B). While only 10 can be assigned to a monthly range (three each to March and September and four to May), 15 are potentially associated with either August or September, three are potentially associated with March, and four had $\delta^{18}O$ values too far from any of the monthly ranges to be potentially assigned. This unit was a key area of focus for Robinson as he theorized the several maxillae belonging to the extinct sea mink (*N. macrodon*) recovered during excavation of this unit had a ritualistic context.

Table 4.3b represents the $\delta^{18}O$ analysis for 18 archaeological shell samples excavated from unit N28 E21; two interannual sequence samples are not included due to damage (ventral margin) or inapplicability (interannual sequence). 12 chondrophores and two ventral margins were selected from levels 1x through 5 from the southeast quad, one chondrophore and two ventral margins from the northeast quad of level 4, and one ventral margin from the northwest quad of level 2 for a total of 26 cm excavation depth below datum. The varying distribution of samples taken per quad is attributed to the loss of samples discussed above. Each level corresponded to 5 cm of depth below datum with the exception of level 5 which was 6 cm below datum. Six of the archaeological samples could be assigned to a monthly range (September (4), March (1), or

April/May (1)), six could potentially be assigned to August or September, one could potentially be assigned to March, one could potentially be assigned to April/May/June, and four could not be assigned to any monthly range. This unit is associated with the largest frequency of European salt-glazed chamber pot excavated from the site.

Table 4.3c represents the $\delta^{18}O$ analysis for nine archaeological shell samples excavated from unit N26 E18. Nine chondrophores were selected from levels 3 through 5a of the southeast quad and represent 15 cm of depth below datum with 5 cm levels. Only two of the archaeological shell samples could be assigned to monthly range (September), but the other seven can potentially be assigned to August or September. This unit is associated with a hearth, lithic manufacturing area, and the second densest frequency of shell thus far excavated from the site.

Table 4.3d represents the $\delta^{18}O$ analysis for 12 archaeological shell samples excavated from unit N53 E30. 12 chondrophores were selected from levels 3 through 6 of the southeast quad (with the exception of one shell from level 3 belonging to the southwest quad), and each level corresponds to 5 cm of depth below datum for a total depth range of 20 cm. Only one sample had an association with any modern monthly range (April and June), but could also potentially be associated with the month of July. The other 11 samples suggest a strong potential to be associated with the months of August and September. This unit is located on the back perimeter of the site and was chosen to determine if seasonality remained consistent across the site.

Archaeological Samples N29 E19																										
			13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	31	83	84	54	85	86	87
Modern Month	**Min d18O**	**Max d18O**	0.2814	0.0196	-0.2545	0.9927	0.3676	0.2204	0.7035	0.7345	0.0657	0.2459	-0.7769	0.4810	0.1163	0.1890	0.8110	0.3147	0.6378	-0.4606	1.0815	0.9899	-0.5739	0.8112	0.7302	1.0762
May (3)	0.89493	1.2073				x											o				x	x		o		x
June (2)	1.27334	1.8299																								
July (1)	1.5034	1.5034																								
August (1)	0.4134	0.4134					o	o						o				o								
September (2)	0.12724	0.22173	o	o	o		o	x			o	o			o	x		o								
October (0)																										
November (4)																										
December (3)																										
January (7)																										
February (3)																										
March (3)	0.8082	0.9381				o			o	o							x					o		x	o	
April (2)	1.2811	1.9262																								

Table 4.3a: Comparison of $\delta^{18}O$ values from N29 E19 against HPBD. See Table 3.2a for provenience information.

			Archaeologicl Samples N28 E21																		
			88	89	67	90	91	92	93	94	95	96	97	98	64	65	66	99	100	101	110
Modern Month	**Min d18O**	**Max d18O**	1.2493	0.6871	0.606	1.1065	-0.1185	-0.0099	0.872	-0.3843	0.4622	0.2171	-0.1181	0.1646	0.5314	0.708	0.1639	0.4573	0.1333	0.6062	0.6153
May (3)	0.89493	1.2073	o			x			o												
June (2)	1.27334	1.8299	o																		
July (1)	1.5034																				
August (1)	0.4134										o				o			o			o
September (2)	0.12724	0.22173					o	o				x	o	x			x		x		
October (0)																					
November (4)																					
December (3)																					
January (7)																					
February (3)																					
March (3)	0.8082	0.9381							x							o					o
April (2)	1.2811	1.9262	o			x															

Table 4.3b: Comparison of $\delta^{18}O$ values from N28 E21 against HPBD. See Table 3.2b for provenience information.

			Archaeological Samples N26 E18													
			111	112	113	114	115	55	56	57	58	59	60	61	62	63
Modern Month	**Min d18O**	**Max d18O**	0.5208	0.0145	0.0357	0.7689	0.2781	0.1586	-0.1332	-0.1043	0.5219	-0.0463	-0.0074	-0.3458	0.1755	0.4818
May (3)	0.89493	1.2073				o										
June (2)	1.27334	1.8299														
July (1)	1.5034															
August (1)	0.4134		o				o				o					o
September (2)	0.12724	0.22173		o	o		o	x	o	o		o	o		x	
October (0)																
November (4)																
December (3)																
January (7)																
February (3)																
March (3)	0.8082	0.9381				o										
April (2)	1.2811	1.9262														

Table 4.3c: Comparison of $\delta^{18}O$ values from N26 E18 against HPBD. See Table 3.2c for provenience information.

			Archaeological Samples N53 E30											
			1	2	3	4	5	6	7	8	9	10	11	12
Modern Month	**Min d18O**	**Max d18O**	0.4343	0.6733	1.5386	0.0988	0.5592	0.3551	0.5616	0.4539	0.4114	-0.0420	0.6218	0.4604
May (3)	0.89493	1.2073												
June (2)	1.27334	1.8299			x									
July (1)	1.5034				o									
August (1)	0.4134		o					o		o	o			o
September (2)	0.12724	0.22173				o		o				o		
October (0)														
November (4)														
December (3)														
January (7)														
February (3)														
March (3)	0.8082	0.9381												
April (2)	1.2811	1.9262			x									

Table 4.3d: Comparison of $\delta^{18}O$ values from N29 E19 against HPBD. See Table 3.2d for provenience information.

4.2 Jones Cove, Maine

Between five to seven modern *M. arenaria* shells were sampled from each month of collection for a total of 60 samples (Appendix A). Research conducted by Newell (1982) indicated that under modern conditions shells in this area generally have a slower average growth rate and do not reach the legal size of two inches (50.8 mm) until age seven; research conducted by Dow and Wallace (1951) indicated that *M. arenaria* from Milbridge, Maine (north of Gouldsboro) take six years to reach 50.8 mm SL and *M. arenaria* from Sullivan, Maine (south of Gouldsboro) take 10 years. As an average is not known for Jones Cove, the same measurement used for the HPBD was used for the JCBD, thus, any shells measuring over 58.95 mm in total SL were not included in this analysis, resulting in only nine usable modern shells. As this dataset is already constrained due to missing samples from the month of October (red tide), the months of February and March (winter ice formation), and because data from the months of November, December, and January are misrepresentative, it is inadvisable to infer the seasonality of this site based on the remaining five $\delta^{18}O$ values. Nevertheless, I present my results as a contribution to further work in this area. A total of 26 $\delta^{18}O$ values were derived from archaeological shell samples from the two available column samples spanning 40 cm of excavation depth below datum (Table 3.3a-b). Tables 4.4a-b represents the $\delta^{18}O$ values derived from the five usable modern shells and the archaeological $\delta^{18}O$ shell values.

			Archaeological Samples N77 E9										
			1	2	3	4	5	6	27	7	8	9	18
Modern Month	**Min d18O**	**Max d18O**	0.5319	1.2887	0.9255	0.6972	1.0945	1.4764	0.7286	-0.2204	0.4846	0.5499	0.4949
August (1)	0.3553		o								o	o	o
September (0)													
October (0)													
November (1)													
December (3)													
January (0)													
February (0)													
March (0)													
April (0)													
May (1)	0.7517		o		o	o			o			o	
June (1)	0.3262		o								o	o	o
July (2)	-0.1990487	-0.11027486								o			

Table 4.4a: Comparison of $\delta^{18}O$ values from N77 E9 column sample against JCBD. See Table 3.3a for provenience information.

			Archaeological Samples N74 E11														
			28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Modern Month	**Min d18O**	**Max d18O**	0.5788	-0.1821	0.2961	0.2063	-0.5685	0.0771	0.5037	0.2172	-1.49	-0.2477	-0.2345	-1.6166	-0.0178	-0.1562	0.3864
August (1)	0.3553				o	o			o	o							
September (0)																	
October (0)																	
November (1)																	
December (3)																	
January (0)																	
February (0)																	
March (0)																	
April (0)																	
May (1)	0.7517		o														
June (1)	0.3262				o	o			o	o							o
July (2)	-0.1990487	-0.11027486		o								o	o		o	o	

Table 4.4b: Comparison of $\delta^{18}O$ values from N74 E11 against HPBD. See Table 3.3 for provenience information.

CHAPTER 5

DISCUSSION

The focus of this research was to conduct an oxygen isotope analysis ($\delta^{18}O$) on *M. arenaria* shell from three archaeological shell midden sites located along the coast of Maine to assess season(s) of occupation. Research has indicated that mollusks record the fluctuating $\delta^{18}O$ ratio of their living environment within the expanding matrix of their shells, but this is only true when they are 1) submerged, and 2) actively growing. As I discovered during my analysis, *M. arenaria* are **not** continuously growing in the Machias Bay or Jones Cove mudflats; they apparently experience a winter shutdown period where little to no growth takes place from November-February/March (Hancock 1982; Beal et al. 2001). Past seasonality studies of archaeological *M. arenaria* using oxygen isotopes have not accounted for this observation and use the $\delta^{18}O$ values derived from modern *M. arenaria* shells collected in the winter months as part of their analyses (Burchell et al. 2014). By not taking this winter shutdown into consideration, the resulting values seem to indicate seasonal fluctuating $\delta^{18}O$ values (Figure 4.1a) when in reality, the $\delta^{18}O$ values obtained from those months actually reflect the $\delta^{18}O$ value prior to the onset of the winter shutdown period. A second consideration not accounted for when using this species is their growth rate and how it is affected by local environment. In the following sections, the variables that contribute to the growth rate of *M. arenaria* are explored and I discuss how these variables affect the results of this analysis.

5.1 Growth rate

The literature review (Chapter 2, Section 2.1) did not indicate that the following variables have been previously considered when using bivalves to infer the seasonality of an archaeological site, and therefore they were not controlled for in the design of the present research. The growth rate of *M. arenaria* is not only affected by water chemistry, but also by location within the tidal gradient, sediment type, water temperature, food availability, predators, age, and the onset of spawning (Newcombe 1935; Dow and Wallace 1957; Commito 1982; Newell 1982; Newell and Hindu 1982; Beal et al. 2001). These variables are explored below in the context of local environmental conditions.

5.1.1 Location within the tidal gradient

While sea surface temperature and salinity levels are two factors discussed when analyzing bivalve shells, specific collection loci (archaeological or modern) are not often noted. Location is a huge factor in the growth rate of *M. arenaria* because they only grow when completely submerged, and not when the mudflat is exposed (Newcombe 1935; Beal et al. 2001; Beal and Otto 2019). *M. arenaria* located near the shore will have a different growth rate than those (of the same age) located in the middle of the mudflat or near the low-tide line because those clams are submerged for longer periods of time (Newcombe 1935; Dow and Wallace 1961:8,12; Newell 1982:10; Beal et al. 2001; Beal and Otto 2019:2). Research conducted by Beal et al. (2001) on 10,080 juvenile *M. arenaria* at a mudflat in Mason's Bay, Maine indicated that the mean shell length (SL) significantly increased with decreasing tidal height and that the greatest amount of shell was added between June and August (Beal et al. 2001:134). It was also found that *M. arenaria* living nearest the shoreline stopped adding shell earlier than *M. arenaria* from the middle and low areas of the mudflat (Beal et al. 2001:161). Archaeologists using $\delta^{18}O$ values derived from bivalves have not accounted for this in the design of their research. To determine the average growth rate for a given month across a mudflat, modern collections should be taken from areas near the shoreline, in the middle of the mudflat, and near the low-tide line. By doing so, it can be ascertained if $\delta^{18}O$ values should be obtained from the ventral margin (if growth rate is high) or through sequential sequencing (if growth rate is low).

5.1.2 Sediment type

The type of sediment in which the bivalves grow (sand, mud, or gravel) has an effect on the growth rate of the shell (Dow and Wallace 1961:10; Newell 1982; Newell and Hindu 1982; Weston and Buttner 2010); *M. arenaria* grow thinner and faster in sand, and thicker/more robust but more slowly in mud and gravel (Dow and Wallace 1961:10; Newell and Hindu 1982:292-293; Weston and Buttner 2010:2). I observed these characteristics in the field; modern shells collected from the Jones Cove mudflats were located in a muddy, gravel matrix and in general had more robust shells compared with shells collected from the Machias Bay mudflat, which were thinner and located in a sandier matrix. It can then be surmised that the modern *M. arenaria* collected from Jones Cove have experienced slower growth and therefore their yearly growth increments will be smaller, increasing the potential to oversample along the ventral margin.

5.1.3 Age

The growth rate of *M. arenaria* in Maine stays fairly consistent throughout its first five years of life and then begins to decrease, adding less shell to its total shell length each consecutive year (Dow and Wallace 1951:7 Dow and Wallace 1957:16; Commito 1982). This raises the question: at what age does the growth increment become too small to be accurately sampled at the ventral margin? To examine this, it is necessary to understand the average growth rate for each local area because every mudflat is exposed to a separate set of environmental conditions. As this is not a variable that has been previously considered when using this species in archaeological $\delta^{18}O$ analysis, it was not controlled for or included in the scope of this research. Fortunately, research conducted by Dow and Wallace (1951) examined growth rates for *M. arenaria* in Holmes Bay (adjacent and connected to Machias Bay), and in Milbridge (north of Gouldsboro) and Sullivan (south of Gouldsboro). The authors found that it takes five years in Holmes Bay, six years in Milbridge, and 10 years in Sullivan to reach 50.8 mm SL (the legal minimum size). Dow and

Wallace also broke the coast of Maine into seven areas and established growth rate averages for those areas; I used the averages from Area II (Cutler to Schoodic Point) in this analysis and determined that *M. arenaria* measuring over 58.95 mm in total SL would not be included in the dataset. This SL was chosen because after this point, the average annual increase in SL for *M. arenaria* significantly decreases with age (Table 5.1) which increases the potential to oversample the ventral margin. Between year one and two, 9.61mm of SL was added; between year two and three, 9.93mm; between year three and four, 9.62mm; between year four and five, 8.91mm; between year five and six, 8.19mm; between year six and seven, 5.7mm; and between year seven and eight, 4.2mm. While these values may seem close to each other, their differences as best displayed visually (Figure 5.1) in order to truly grasp its significance.

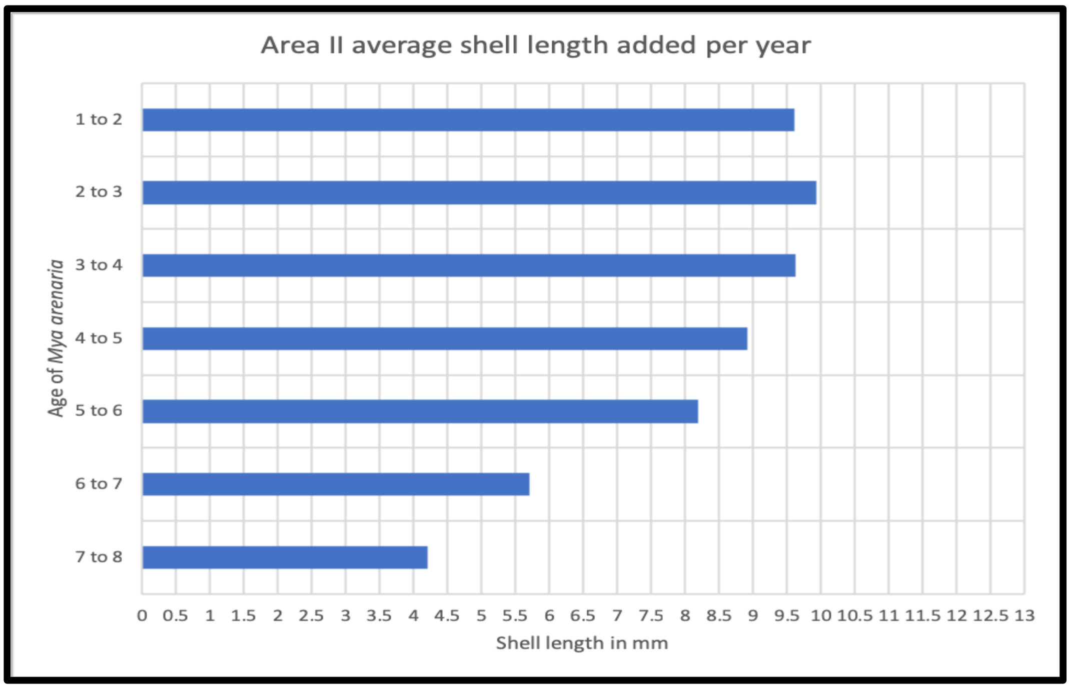

Fig 5.1. Depicts how much shell is added to the bivalve's total shell length each year based on Dow and Wallace 1951. By year eight, it is adding about half as much shell as in years two, three, and four. *Not to scale.

	AREA I	AREA II	AREA III	AREA IV	AREA V	AREA VI	AREA VII
Mean Age (Yrs.)	Mean Size in mm.	Mean Size in mm.	Mean Size in mm.	Mean Size in mm.	Mean Size in mm.	Mean Size in mm.	Mean Size in mm.
1	12.57	12.69	11.59	16.02	10.85	18.45	19.49
2	22	22.3	18.71	22.49	21.7	34.89	32.89
3	29.23	32.23	26.43	28.65	32.62	44.58	43.56
4	35.15	41.85	35.88	35.47	43.9	50.13	52.18
5	40.53	50.76	42.27	42.44	50.6	52.31	57.46
6	40.93	58.95	47.3	49	56.15	49.72	62.09
7	45.86	64.65	52.31	53.46	53	48.47	55.05
8	50.07	68.85	57.18	58.08		51.4	57.41
9	55	76.2	64.15	63.5		53.6	58.9
10	58.75	82.37	65.82	70.4		61.83	68.03
11	64.4	99	55.09	77.6		52	75
12	67.75		58.73	81.5		65	
13			62.3			68	

Table 5.1: Summary table of average shell length corresponding to age for *M. arenaria* along the coast of Maine adapted from Dow and Wallace (1951). *Soft shell clam growth rates in Maine*. Area II was used in this research.

5.1.4 Water temperature and spawning

Both spawning and water temperature affect growth rate in *M. arenaria*. In Maine, spawning takes place between June and September (Dow and Wallace 1961:11) when water temperatures reach above 10°C (Weston and Buttner 2010:2). During this time, energy is diverted from shell growth to spawning activities, but it is also at this time when this species is growing most rapidly. A second effect of spawning on growth rate is that as these bivalves age, they focus more energy on spawning than on growth (Commito 1982:187), creating another reason to caution against using larger clams in $\delta^{18}O$ analyses of this species. In terms of water temperature, warmer conditions favor rapid growth (Dow and Wallace 1961:11) up to a point above which higher temperatures may be detrimental.

5.1.5 Current, food availability, and degree of crowding

Without a strong current, too many bivalves inhabiting one area of a mudflat creates competition for food and increases concentration of waste products (Dow and Wallace 1961:12; Newell and Hindu 1982:7). Individuals located closer to shore not only have less time to feed, but also face decreased food availability. These factors can affect growth rate.

5.1.6 Chondrophore size

As the majority of the archaeological $\delta^{18}O$ values were derived from chondrophores, I took measurements of the chondrophores of modern shells and used them to establish size ranges that could be associated with SL. However, to my knowledge, no prior research has been done on this topic and therefore I did not apply a chondrophore/SL ratio to the results; this approach warrants further consideration. At least three modern shells from every month had both the chondrophore and ventral margin sampled, for a total of 44 shells, however, only 26 shells had a SL that measured less than 58.95 mm. In comparing the $\delta^{18}O$ values from the chondrophores and ventral margins of these shells, I found that only nine were within 0.25‰ of each other, well within the range margin associated with each modern month; because this equates to an accuracy of 34.6% any conclusions based on these data are tentative at best. To further this line of thought, by extrapolating the range of modern chondrophore length for SLs between 40-50 mm, 50-60 mm and 60+ mm, I found that chondrophores measuring over 9.72 mm corresponded to SL over 60 mm, and therefore could not be used. In measuring the archaeological chondrophores used, it was found that 43 from 62-8 and a minimum of four from 44-13 were too large; the samples from 62-6 were not kept separate, and samples from the second column sample from 44-13 are currently misplaced, so measurements could not be taken. Additionally, 10 chondrophores from 62-8 and five from 44-13 were broken at the umbo and could not be fully measured.

5.2 Other Potential Sources of Error

5.2.1 Remodeling

M. arenaria is particularly susceptible to breakage and remodeling due, in part, to its fragile shell matrix. When the ventral margins of *M. arenaria* shells are damaged, they are remodeled using the calcium carbonate within their shells and could provide false signals when sampled. If a ventral margin were sampled but was damaged, this has implications for the validity of the results. I did not consider this aspect during the initial sampling of these datasets, but upon later inspection of the ventral margins using a microscope I determined that several shells from Machias Bay and Jones Cove exhibited damage to the ventral margin of the shells.

5.2.2 Radiocarbon dating and water temperature

When using radiocarbon dates in an archaeological setting, it is important to understand the context from which the samples were derived. In the case of shell middens, when using this method to date a shell, not only does the archaeological context of the shell matter (depth, location, and proximity to identifiable artifacts) but a marine reservoir effect must be applied. Ideally, if archaeological shells are used in a $\delta^{18}O$ analysis, they would be selected from the same level and unit as radiocarbon dated organic remains (preferably carbonized twigs or seeds) or shell (if available) to provide additional temporal context.

There have been eight radiocarbon dates obtained for 62-8 with two from shell samples, all processed at Beta Analytic, Inc. Both of the dated shell samples were *M. arenaria* shells and were taken from burned areas in Features 21 and 28. The shell from Feature 28 (PN 3610.1) has a date of 1260 +/- 30 calibrated years BP (1095-1310 calibrated year AD), and the shell from Feature 21 (PN 2938.1) has a date of 745-555 calibrated years BP (1205-1395 calibrated years

AD). Both samples have been adjusted for the local marine reservoir effect. As these are the only two shell samples that have been dated for this site, their dates cannot define an age bracket for the midden, but they do fall within the range of the Medieval Climate Anomaly which is noteworthy as the water was warmer during this period of time and would alter the ratio of oxygen isotopes found within the shells.

To date, there is not a reliable record of past sea surface temperature for the Gulf of Maine, but research on this matter is currently underway (i.e., Wanamaker et al., 2008; 2011). Until a reliable record is produced, and corrections can be applied, for the purposes of this analysis, I was advised to assume no large variations in sea surface temperature or salinity levels have taken place during the time these middens were in use. By doing so, a direct comparison between modern and archaeological samples can be made, but it is not clear what corrections would be necessary if the archaeological shells had been dated to the Little Ice Age when temperatures were colder than they are today.

5.2.3 Equipment and modern collection procedure

A garden hoe and a cooler (Figure 3.1) were used to collect and transport modern *M. arenaria* shell samples. Samples were boiled to remove the soft tissues. This cooking process does not modify the chemistry of the shell (Müller et al. 2016:2) and is therefore permissible to use; traditional techniques involve shucking and air-drying. In retrospect, the author advises against using a garden hoe as a means to dig up clams, at least in terms of this type of analysis, because of the likelihood of damaging the ventral margin of the mollusks. Although more time consuming, digging while wearing protective rubber gloves is a more advisable method. Water collection should also be done in conjunction with bivalve collection in order to construct a monthly water temperature profile for the environment the mollusks are living in.

5.3 Conclusion

The original intent of this research was to perform an oxygen isotopic analysis to infer the season of occupation at three archaeological shell midden sites; a secondary intent was to provide evidence in support of, or to test Sanger's (1982) hypothesis of continuous coastal occupation. As the research progressed to the analysis phase, noise within the modern datasets required altering the original intent. The noise is not a result of the methodology per se, but rather applying it to this species in the context of a seasonality analysis. Too many assumptions have been made by archaeologists without considering the interacting variables of this type of research, such as evidenced by the variables discussed above and reiterated in Table 5.2 below. That being said, I do not believe that it was the intent of the authors who have published articles using this methodology to mislead. I instead suggest this research has suffered from the lack of specialized knowledge required to understand the complexities of analyzing bivalve remains in this way. Not only are modern and archaeological samples required to perform these analyses, but a deep knowledge and understanding of the species used, its interactions with the surrounding environment, and a record of past seasonal fluctuations are necessary to make such interpretations.

Variable	Problem	Proposed Solution
Growth Rate	• Is not continuous throughout the calendar year. • Decreases with age.	• Know shutdown period for clam flat in use. • Know the average growth rate for clam flat in use so that SL can be controlled.
Location within the tidal gradient	• Shells only grow when fully submerged. • Shells (of same age) located near the shoreline are smaller than those in the middle of the flat and those located at the low tide mark.	• Collect mollusks throughout the tidal gradient (close to shoreline, mid-flat, low tide mark) during each monthly collection to create an average expected $\delta^{18}O$ range associated with each month.
Sediment type	• Thinner but faster growth = sand; thicker/more robust but slow growth = mud/gravel	• Know the sediment matrix for the clam flat in use as the growth rate varies with sediment type.
Age	• Total shell length added per year decreases with age	• Must know the average growth rate of the mollusks living within the mudflat associated with the archaeological site being analyzed. • The larger the clam, the older and slower it grows. • Less total SL added per year increases the likelihood of sampling too much along the ventral margin.
Water temperature and onset of spawning	• When water temperatures reach above 10°C, energy is diverted from shell growth to spawning. • Older mollusks, in general, focus more energy on spawning than growth.	• Keep track of coastal water temperatures. • The use of smaller shells versus larger shells is recommended.

Table 5.2 continued

Water current, food availability, and degree of crowding	• Strong current = less crowding = increased food availability. • Mollusks closer to shore have less time to feed = decreased food availability.	• Understand the environmental context the mollusks are living in as it affects the growth rate of these mollusks. • A mollusk can only feed when it is submerged, therefore, those closer to shore have less food availability which leads to smaller increases of total SL added per year.
Chondrophore size	• Measuring the length of the chondrophore to extrapolate total SL warrants further research, if shown to be true, it will be very useful as most archaeological samples used in this research were derived from chondrophores, and there is no way (currently) to determine if they are too old/large to provide good data.	• Further research is required to determine if there is a correlation between chondrophore length and SL.
Remodeling	• The ventral margins are highly susceptible to breakage, if the ventral margin is remodeled it would provide a false signal.	• Sequential samples leading up to the ventral margin would help to determine if remodeling has occurred. • Further testing of the validity of $\delta^{18}O$ values derived from the chondrophore is required to determine if they would provide more reliable data then the ventral margin.

Table 5.2 continued

Radiocarbon dating and water temperature	● Understanding the context of radiocarbon dates. ● Adjusting for the marine reservoir effect. ● Being aware of climatic variabilities as they pertain to heating or cooling of the ocean which changes the $\delta^{18}O$ of the water.	● If possible, sampled shells should be taken from the same context as the radiocarbon dated material to allow for inferences about the shell to be drawn. ● If radiocarbon dates are taken from shells, must not only correct for the marine reservoir effect, but also check the dates against known periods of oceanic warming and cooling as that will affect the $\delta^{18}O$ values.
Equipment and collection procedure	● To prevent damage to the ventral margin, mollusks should be dug out wearing protective rubber gloves. ● Water samples should be taken at the same time as mollusk collection.	● Advises against using a garden hoe or clam rake to collect modern mollusks. ● Must have a means to keep samples collected from different locations within the tidal gradient and different sites separate. ● Water samples collected at the time of mollusk collection can be used to create a water temperature profile.

Table 5.2: Summarizes the variables, problems, and proposed solutions that are relevant to carrying out a seasonality analysis using *M. arenaria*.

Based on the aforementioned challenges and small amount of usable data, it is not advisable to make a confident seasonality assessment using this combination of data and methodology for 62-6, 62-8, and 44-13. It is my hope that the challenges outlined here have brought attention to the complexities of using this methodology, and that the variables explored above will be taken into consideration by future researchers when using oxygen isotopes to infer the seasonality of other archaeological shell midden sites.

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APPENDIX A

All modern *M. arenaria* shells sampled at Machias Bay

Sample Identifier	$\delta^{18}O$ value	Modern Month	Sample Location	Set Number	Shell Length (mm)	Shell Height (mm)	Chondrophore Length (mm)	Notes
HP_160001	0.89493	May-16	Ventral Margin	1	46.70	31.49	8.23	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_160010	1.27028	May-16	Ventral Margin	4	69.6	39.54	11.09	Shell has separation along the ventral margin; all measurements reflect minimum values.
HP_160019	1.46427	May-16	Ventral Margin	3	48.6	29.72		All measurements reflect minimum values.
HP_160040	0.7602	May-16	Chondrophore	3			8.01	All measurements reflect minimum values.
HP_0085	0.1202	May-16	Ventral Margin	6	58.23	35.27		Damage to ventral margin; growth line visible; sampled too much; all measurements reflect minimum values.
HP_0086	0.852	May-16	Chondrophore	6			9.72	All measurements reflect minimum values.
HP_0087	1.0663	May-16	Ventral Margin	12	60.16	35.61		All measurements reflect minimum values.
HP_0088	1.0758	May-16	Chondrophore	12			8.45	All measurements reflect minimum values.
HP_0089	1.2073	May-16	Ventral Margin	7	57.62	35.66		Damage to ventral margin; growth line visible; all measurements reflect minimum values.
HP_0090	1.0115	May-16	Chondrophore	7			8.19	All measurements reflect minimum values.
HP_0001	0.8295	May-16	Ventral Margin	2	60.81	37.32	10.65	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_160028	1.33888	Jun-16	Ventral Margin	6	62.62	37.61		Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_160029	1.56595	Jun-16	Chondrophore	6			10.01	All measurements reflect minimum values.
HP_160030	1.27334	Jun-16	Ventral Margin	1	54.27	32.78	umbo broken	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_160039	1.39034	Jun-16	Ventral Margin	8	61.87	36.28	9.81	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_0071	1.596	Jun-16	Ventral Margin	9	59.86	34.76		All measurements reflect minimum values.

Table A1 continued

HP_0072	1.482	Jun-16	Chondrophore	9			8	All measurements reflect minimum values.
HP_0073	1.8265	Jun-16	Ventral Margin	4	60.94	37.5		All measurements reflect minimum values.
HP_0074	0.6584	Jun-16	Chondrophore	4			10	All measurements reflect minimum values.
HP_0075	1.8299	Jun-16	Ventral Margin	2	57.88	35.32		Damage to ventral margin; all measurements reflect minimum values.
HP_0076	1.3122	Jun-16	Chondrophore	2			9	All measurements reflect minimum values.
HP_160041	1.3042	Jul-16	Ventral Margin	2	68.13	38.32	9.6	All measurements reflect minimum values.
HP_160050	0.69889	Jul-16	Ventral Margin	3	57.92	33.28		Damage to ventral margin; all measurements reflect minimum values.
HP_160051	0.10288	Jul-16	Chondrophore	3			7.62	All measurements reflect minimum values.
HP_160052	0.4832	Jul-16	Ventral Margin	8	50.1	30.43	broken	Damage to ventral margin; all measurements reflect minimum values.
HP_0077	1.605	Jul-16	Ventral Margin	14	72.55	38.5		Chondrophore has a fractured edge; all measurements reflect minimum values.
HP_0078	0.7845	Jul-16	Chondrophore	14			9.52	All measurements reflect minimum values.
HP_0079	1.5034	Jul-16	Ventral Margin	12	53.72	33.67		All measurements reflect minimum values.
HP_0080	0.9162	Jul-16	Chondrophore	12			umbo broken	
HP_0081	1.4089	Jul-16	Ventral Margin	10	68.83	39.86		All measurements reflect minimum values.
HP_0082	1.0119	Jul-16	Chondrophore	10			9.25	All measurements reflect minimum values.
HP_0002	0.3297	Jul-16	Chondrophore	1			9.31	All measurements reflect minimum values.
HP_0003	0.7424	Jul-16	Ventral Margin	1	63.22	39.31		All measurements reflect minimum values.
HP_160065	0.52837	Aug-16	Ventral Margin	4	75.69	42.5	11.5	Damage to umbo; all measurements reflect minimum values.
HP_160074	-0.00563	Aug-16	Ventral Margin	6	53.83	32.34	6.99	Damage to ventral margin; all measurements reflect minimum values.
HP_160075	0.1994	Aug-16	Ventral Margin	1	60.43	36.29		All measurements reflect minimum values.
HP_160076	0.40728	Aug-16	Chondrophore	1			8.86	All measurements reflect minimum values.
HP_0012	0.7668	Aug-16	Ventral Margin	7	61.06	37.38		All measurements reflect minimum values.
HP_0013	0.4652	Aug-16	Chondrophore	7			7.55	All measurements reflect minimum values.
HP_0014	0.7865	Aug-16	Ventral Margin	3	80.17	48.27		All measurements reflect minimum values.

Table A1 continued

HP_0015	0.6242	Aug-16	Chondrophore	3			11.28	All measurements reflect minimum values.
HP_0083	0.4134	Aug-16	Ventral Margin	2	54.59	31.84		All measurements reflect minimum values.
HP_0084	-0.2179	Aug-16	Chondrophore	2			6.66	All measurements reflect minimum values.
HP_0004	0.6971	Aug-16	Ventral Margin	5	67.86	38.56	umbo fractured	All measurements reflect minimum values.
HP_160053	0.12724	Sep-16	Ventral Margin	3	56.46	33.31	broken	Damage to ventral margin; all measurements reflect minimum values.
HP_160054	-0.00684	Sep-16	Chondrophore	5			broken	
HP_160055	-0.02187	Sep-16	Ventral Margin	5	60.44	36.8		All measurements reflect minimum values.
HP_160056	0.22173	Sep-16	Ventral Margin	7	57.74	35.22.	8.17	All measurements reflect minimum values.
HP_0016	0.9321	Sep-16	Ventral Margin	4	63.45	36.78		All measurements reflect minimum values.
HP_0017	0.36	Sep-16	Chondrophore	4			9.96	All measurements reflect minimum values.
HP_0018	0.9253	Sep-16	Ventral Margin	6	68.91	38.95		All measurements reflect minimum values.
HP_0019	0.7025	Sep-16	Chondrophore	6			9.81	All measurements reflect minimum values.
HP_0020	0.8029	Sep-16	Ventral Margin	2	64.26	36.96		All measurements reflect minimum values.
HP_0021	0.4297	Sep-16	Chondrophore	2			10.36	All measurements reflect minimum values.
HP_160077	0.28751	Nov-16	Ventral Margin	14	62.02	37.98	11.64	All measurements reflect minimum values.
HP_160086	0.30131	Nov-16	Ventral Margin	4	52.55	30.87		All measurements reflect minimum values.
HP_160087	0.55039	Nov-16	Chondrophore	4			8.89	All measurements reflect minimum values.
HP_160088	1.18196	Nov-16	Ventral Margin	11	50.74	29.78	8.37	Sampled too much; all measurements reflect minimum values.
HP_0022	1.1121	Nov-16	Ventral Margin	19	54.04	34.55		Sampled too much; all measurements reflect minimum values.
HP_0023	-1.0079	Nov-16	Chondrophore	19			8.71	All measurements reflect minimum values.
HP_0024	0.8975	Nov-16	Ventral Margin	17	55.06	33.41		Sampled too much; all measurements reflect minimum values.
HP_0025	0.1565	Nov-16	Chondrophore	17			8.22	All measurements reflect minimum values.
HP_0026	1.1852	Nov-16	Ventral Margin	5	61.85	37.55		All measurements reflect minimum values.
HP_0027	0.814	Nov-16	Chondrophore	5			10.93	All measurements reflect minimum values.
HP_0005	0.7764	Nov-16	Ventral Margin	18	57.49	34.35	8.79	Sampled too much; all measurements reflect minimum values.

Table A1 continued

HP_160091	2.02933	Dec-16	Ventral Margin	4	61.27	38.11	10.14	All measurements reflect minimum values.
HP_160100	1.42113	Dec-16	Ventral Margin	2	56.74	36.19		Sampled too much; all measurements reflect minimum values.
HP_160101	1.28764	Dec-16	Chondrophore	2			8.75	All measurements reflect minimum values.
HP_160102	1.90566	Dec-16	Ventral Margin	7	59.21	35.99	9.54	All measurements reflect minimum values.
HP_0028	0.9392	Dec-16	Ventral Margin	3	52.94	31.9		Sampled too much; all measurements reflect minimum values.
HP_0029	-0.3167	Dec-16	Chondrophore	3			7.73	All measurements reflect minimum values.
HP_0030	1.2791	Dec-16	Ventral Margin	10	60.22	37.3		All measurements reflect minimum values.
HP_0031	0.8567	Dec-16	Chondrophore	10			9.26	All measurements reflect minimum values.
HP_0032	0.7935	Dec-16	Ventral Margin	5	48.23	28.58		All measurements reflect minimum values.
HP_0033	0.7267	Dec-16	Chondrophore	5			7.2	All measurements reflect minimum values.
HP_0006	1.7289	Dec-16	Ventral Margin	11	62.7	37.78	10.83	All measurements reflect minimum values.
HP_170103	1.56537	Jan-17	Ventral Margin	2	55.51	34.84		Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_170112	1.03221	Jan-17	Chondrophore	2			8.81	All measurements reflect minimum values.
HP_170113	0.82309	Jan-17	Ventral Margin	8	44.49	26.29	6.88	All measurements reflect minimum values.
HP_170114	1.48085	Jan-17	Ventral Margin	9	48.13	27.67	7.58	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_0034	1.5777	Jan-17	Ventral Margin	15	51.22	31.06		Damage to ventral margin; all measurements reflect minimum values.
HP_0035	0.5198	Jan-17	Chondrophore	15			7.79	All measurements reflect minimum values.
HP_0036	1.1146	Jan-17	Ventral Margin	6	49.2	30.53		Damage to ventral margin; all measurements reflect minimum values.
HP_0037	0.814	Jan-17	Chondrophore	6			broken	
HP_0038	1.5855	Jan-17	Ventral Margin	16	55.69	32.15		Sampled too much; all measurements reflect minimum values.
HP_0039	1.3825	Jan-17	Chondrophore	16			8.88	All measurements reflect minimum values.
HP_0007	1.932	Jan-17	Ventral Margin	11	57.55	35.14	9.61	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.

Table A1 continued

HP_170115	0.41249	Feb-17	Ventral Margin	9	56.81	36.63		Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; growth line visible; all measurements reflect minimum values.
HP_170124	0.72921	Feb-17	Chondrophore	9			8.73	All measurements reflect minimum values.
HP_170125	0.77407	Feb-17	Ventral Margin	7	59	34.94	8.2	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_170126	0.45836	Feb-17	Ventral Margin	10	44.88	28.98	umbo broken	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_0043	1.5453	Feb-17	Ventral Margin	11	57.12	32.49		Growth line visible; all measurements reflect minimum values.
HP_0044	0.5112	Feb-17	Chondrophore	11			7.4	All measurements reflect minimum values.
HP_0045	0.6223	Feb-17	Ventral Margin	12	46.56	28.04		Growth line visible; all measurements reflect minimum values.
HP_0046	1.1025	Feb-17	Chondrophore	12			broken	
HP_170127	0.92592	Mar-17	Ventral Margin	6	49.64	28.81	7.39	Growth line visible; all measurements reflect minimum values.
HP_170136	0.11559	Mar-17	Ventral Margin	1	60.36	36.06		Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_170137	0.53372	Mar-17	Chondrophore	1			10.64	All measurements reflect minimum values.
HP_170138	-3.86523	Mar-17	Ventral Margin	8	46.64	29.64	7.41	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_0047	1.2217	Mar-17	Ventral Margin	2	56.74	34.62		Growth line visible; sampled too much; all measurements reflect minimum values.
HP_0048	0.5994	Mar-17	Chondrophore	2			9.35	All measurements reflect minimum values.
HP_0049	1.473	Mar-17	Ventral Margin	4	56.02	34.77		Growth line visible; sampled too much; all measurements reflect minimum values.
HP_0050	1.2354	Mar-17	Chondrophore	4			9.57	All measurements reflect minimum values.
HP_0051	0.9381	Mar-17	Ventral Margin	10	47.96	27.11		Damage to ventral margin; growth line visible; all measurements reflect minimum values.
HP_0052	0.9357	Mar-17	Chondrophore	10			6.69	All measurements reflect minimum values.

Table A1 continued

HP_0008	0.4463	Mar-17	Ventral Margin	13	58.51	34.49		Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; growth line visible; all measurements reflect minimum values.
HP_0009	sample too small	Mar-17	Chondrophore	13			8.65	All measurements reflect minimum values.
HP_0010	0.8082	Mar-17	Ventral Margin	12	44.7	29.17	7.47	All measurements reflect minimum values.
HP_170139	0.6273	Apr-17	Ventral Margin	3	56.82	33.28		Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_170148	0.47567	Apr-17	Chondrophore	3			broken	
HP_170149	0.47899	Apr-17	Ventral Margin	4	40.53	24.72	7.16	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
HP_170150	0.02868	Apr-17	Ventral Margin	7	46.0	27.6	8.33	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; growth line visible; all measurements reflect minimum values.
HP_0053	0.9208	Apr-17	Ventral Margin	1	58.73	37.89		Damage to ventral margin; all measurements reflect minimum values.
HP_0054	1.0038	Apr-17	Chondrophore	1			umbo broken	
HP_0055	1.9262	Apr-17	Ventral Margin	6	41.38	26.53	7.37	Growth line visible; all measurements reflect minimum values.
HP_0056	0.7187	Apr-17	Chondrophore	6			7.37	All measurements reflect minimum values.
HP_0057	1.2811	Apr-17	Ventral Margin	5	46.91	28.54		Growth line visible; all measurements reflect minimum values.
HP_0058	0.0993	Apr-17	Chondrophore	5			7.52	All measurements reflect minimum values.
HP_0011	0.1925	Apr-17	Ventral Margin	12	46.49	29.85	7.56	Damage to ventral margin; all measurements reflect minimum values.

Table A1: HPBD *M. arenaria* shells sampled.

All modern Jones Cove *M. arenaria* shells sampled.

Sample ID	$\delta^{18}O$ values	Modern Month	Sample Location	Set Number	Shell Length (mm)	Shell Height (mm)	Chondrophore Length (mm)	Notes
JC_160001	0.2158	8/24/16	Ventral Margin	5	72.66	45.08	13.43	All measurements reflect minimum values.
JC_160010	0.02167	8/24/16	Ventral Margin	3	65.57	37.29	7.52	All measurements reflect minimum values.
JC_160011	0.60293	8/24/16	Chondrophore	14			14.54	All measurements reflect minimum values.
JC_160012	-0.51875	8/24/16	Ventral Margin	14	84.14	52.2		Damage to ventral margin; all measurements reflect minimum values.
JC_1	0.3553	8/24/16	Ventral Margin	10	52.6	30.29	7.59	All measurements reflect minimum values.
JC_16	0.945	8/24/16	Ventral Margin	16	74.93	45.99	12.56	All measurements reflect minimum values.
JC_17	1.0647	8/24/16	Ventral Margin	1	71.46	44.29	13.06	Shell warped; all measurements reflect minimum values.
JC_18	0.546	8/24/16	Ventral Margin	17	92.87	52.61	13.57	All measurements reflect minimum values.
JC_160013	0.0377	9/16/16	Ventral Margin	1	74.46	47.89	12.37	All measurements reflect minimum values.
JC_160022	-0.10006	9/16/16	Ventral Margin	4	75.36	44.15	11.23	All measurements reflect minimum values.
JC_160023	-0.45922	9/16/16	Ventral Margin	2	60			Unsure of species.
JC_160024	0.13471	9/16/16	Chondrophore	2			umbo broken	
JC_19	-0.3509	9/16/16	Ventral Margin	5	59.24	33.66		All measurements reflect minimum values.
JC_20	-0.0111	9/16/16	Ventral Margin	3	70	40.34	11.6	Damage to ventral margin; all measurements reflect minimum values.
JC_160025	0.76939	11/19/16	Ventral Margin	1	90.49	50.55	14.38	All measurements reflect minimum values.
JC_160034	1.53116	11/19/16	Ventral Margin	11	59.15	35.74	8.73	All measurements reflect minimum values.
JC_160035	0.27942	11/19/16	Ventral Margin	2	84.93	51.89		All measurements reflect minimum values.
JC_160036	1.06296	11/19/16	Chondrophore	2			14.12	All measurements reflect minimum values.
JC_2	1.5511	11/19/16	Ventral Margin	8	56.74	31.98	7.37	All measurements reflect minimum values.

Table A2 continued

JC_21	0.7467	11/19/16	Ventral Margin	5	79.38	49.9	13.52	All measurements reflect minimum values.
JC_22	0.5059	11/19/16	Ventral Margin	9	72.61	warped	12.05	All measurements reflect minimum values.
JC_23	0.9355	11/19/16	Ventral Margin	13	72.37	47.13	13.28	All measurements reflect minimum values.
JC_160037	0.24642	12/31/16	Ventral Margin	8	69.44 min	42.52	broken umbo	Damage to ventral margin; all measurements reflect minimum values.
JC_160046	1.21853	12/31/16	Ventral Margin	5	53.57	31.18	7.78	All measurements reflect minimum values.
JC_160047	0.48543	12/31/16	Ventral Margin	2	82.55	48.97		All measurements reflect minimum values.
JC_160048	1.30047	12/31/16	Chondrophore	2			13.58	All measurements reflect minimum values.
JC_3	2.2171	12/31/16	Ventral Margin	6	49.55	29.29	7.47	Shell warped; all measurements reflect minimum values.
JC_24	1.2119	12/31/16	Ventral Margin	4	76.2	warped	12.11	All measurements reflect minimum values.
JC_25	1.6597	12/31/16	Ventral Margin	1	46.37	28.68	7.5	Damage to ventral margin; all measurements reflect minimum values.
JC_26	2.2	12/31/16	Ventral Margin	3	48.29	36.35	7.81	All measurements reflect minimum values.
JC_170049	1.0421	1/21/17	Ventral Margin	6	67.21 min	44.35	11.27	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
JC_170058	0.05826	1/21/17	Ventral Margin	10	64.68 min	36.73	9.88	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
JC_170059	1.09807	1/21/17	Ventral Margin	9	66.78 min	40.44		Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
JC_170060	1.18643	1/21/17	Chondrophore	9			12.09	All measurements reflect minimum values.
JC_4	0.3924	1/21/17	Ventral Margin	5	65.61	41.49	10.58	Damage to ventral margin; all measurements reflect minimum values.

Table A2 continued

JC_101	0.8259040	1/21/17	Ventral Margin	1	74.54 min	45.72	Umbo broken	Shell warped; all measurements reflect minimum values.
JC_102	1.9102420	1/21/17	Ventral Margin	2	73.98	43.23	12.92	All measurements reflect minimum values.
JC_103	1.5205	1/21/17	Ventral Margin	4	58.96 min	38.95	9.71	Damage to ventral margin; all measurements reflect minimum values.
JC_170061	1.36747	4/15/17	Ventral Margin	8	68.64	47.38	12.61	All measurements reflect minimum values.
JC_170070	1.4394	4/15/17	Ventral Margin	2	61.97	35.55	umbo broken	All measurements reflect minimum values.
JC_170071	2.413	4/15/17	Ventral Margin	5	60.78	35.5		All measurements reflect minimum values.
JC_170072	2.0665	4/15/17	Chondrophore	5			8.06	All measurements reflect minimum values.
JC_5	1.5829	4/15/17	Ventral Margin	10	84.93	52.51 min		Shell warped; all measurements reflect minimum values.
JC_6	0.6007	4/15/17	Chondrophore	10			13.68	All measurements reflect minimum values.
JC_004	2.1314	4/15/17	Ventral Margin	6	66.26	38.62	8.26	Damage to ventral margin; all measurements reflect minimum values.
JC_005	2.3046	4/15/17	Ventral Margin	9	71.16	39.18	9.56	All measurements reflect minimum values.
JC_006	2.5483	4/15/17	Ventral Margin	7	71.98	44.28	umbo broken	All measurements reflect minimum values.
JC_170073	no peaks	5/20/17	Ventral Margin	3	88.9	54	14.92	All measurements reflect minimum values.
JC_170082	0.2762	5/20/17	Ventral Margin	8	60.96	38.07	umbo broken	Damage to ventral margin; all measurements reflect minimum values.
JC_170083	0.4129	5/20/17	Ventral Margin	1	84.93	53.42		All measurements reflect minimum values.
JC_170084	1.7105	5/20/17	Chondrophore	1			umbo broken	
JC_7	0.1787	5/20/17	Ventral Margin	2	82.55	49.61		All measurements reflect minimum values.
JC_8	sample too small	5/20/17	Chondrophore	2				
JC_007	0.7517	5/20/17	Ventral Margin	5	56.57	33.5	6.67	All measurements reflect minimum values.

Table A2 continued

JC_008	1.086	5/20/17	Ventral Margin	9	56.14	32.93	5.97	Damage to ventral margin; all measurements reflect minimum values.
JC_009	0.7329	5/20/17	Ventral Margin	10	47.75	broken	6.53	Damage to ventral margin; all measurements reflect minimum values.
JC_170085	-0.0649	6/17/17	Ventral Margin	5	75.56	46.77		All measurements reflect minimum values.
JC_170094	-0.2275	6/17/17	Chondrophore	5			12.33	All measurements reflect minimum values.
JC_170095	-3.1336	6/17/17	Ventral Margin	7	broken	31.36	6.38	All measurements reflect minimum values.
JC_9	0.3262	6/17/17	Ventral Margin	1	58.86	35.7		All measurements reflect minimum values.
JC_10	-0.3351	6/17/17	Chondrophore	1			7.82	All measurements reflect minimum values.
JC_11	0.2122	6/17/17	Ventral Margin	9	61.44	36.51	9.21	All measurements reflect minimum values.
JC_010	0.3476	6/17/17	Ventral Margin	2	70.06	40.35	10.97	Damage to ventral margin; all measurements reflect minimum values.
JC_011	0.3513	6/17/17	Ventral Margin	10	no body, can't use			
JC_012	0.869	6/17/17	Ventral Margin	4	79.38	48.78	13.06 min	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
JC_170096	-23.7752	7/22/17	Ventral Margin	7	90.49 min	50.56	14.12	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
JC_170105	-0.3897	7/22/17	Ventral Margin	4	71.06 min	40.18	9.69	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
JC_170106	-31.5171	7/22/17	Ventral Margin	1	84.14 min	50.05	12.39	Shell was resampled by Pontbriand; $\delta^{18}O$ value reflects original sample; all measurements reflect minimum values.
JC_170107	-1.1682	7/22/17	Chondrophore	1			12.39	All measurements reflect minimum values.

Table A2 continued

JC_12	-0.5159	7/22/17	Ventral Margin	5	very broken	shattered	6.69	Damage to ventral margin; all measurements reflect minimum values.
JC_13	-0.1694	7/22/17	Ventral Margin	8	92.25	58.49		All measurements reflect minimum values.
JC_14	-0.4384	7/22/17	Chondrophore	8			15.63	All measurements reflect minimum values.
JC_105	-0.199	7/22/17	Ventral Margin	2	48.63	30.94	7.46	Damage to ventral margin; all measurements reflect minimum values.
JC_106	-0.0901	7/22/17	Ventral Margin	3	67.84	warped	14.41	Damage to ventral margin; all measurements reflect minimum values.
JC_107	-0.1103	7/22/17	Ventral Margin	6	51.95	32.16	6.53	Damage to ventral margin; all measurements reflect minimum values.

Table A2: JCBD *M. arenaria* shells sampled.

APPENDIX B

Site 62-6: unit N47 W19

Sample ID	δ1⁸O value	Sample Location	Unit	Column	Quad	Level	Depth Below Datum (cm)
HPE_0001	0.4701	Chondrophore	N47 W19	1	SE	2	170-175
HPE_0002	0.1652	Chondrophore	N47 W19	1	SE	2	170-175
HPE_0003	0.4162	Chondrophore	N47 W19	1	SE	2	170-175
HPE_0004	-0.1917	Chondrophore	N47 W19	1	SE	3	175-180
HPE_0005	0.2819	Chondrophore	N47 W19	1	SE	3	175-180
HPE_0006	0.0351	Chondrophore	N47 W19	1	SE	3	175-180
HPE_0007	0.5783	Chondrophore	N47 W19	1	SE	4	180-185
HPE_0008	0.1668	Chondrophore	N47 W19	1	SE	4	180-185
HPE_0009	0.2091	Chondrophore	N47 W19	1	SE	4	180-185
HPE_0010	-0.1282	Chondrophore	N47 W19	1	SE	5	185-190

Table B1: Holmes Point East archaeological *M. arenaria* sampled from N47 W19.

Site 62-8: unit N29 E19

Sample ID	$\delta^{18}O$ Value	Sample Location	Drill Increment	Unit	Quad	Level	Depth Below Datum (cm)	Catalog #
HPW_0013	0.2814	Chondrophore	NA	N29 E19	NE	1x	217-225	PN 3312.5
HPW_0014	0.0196	Chondrophore	NA	N29 E19	NE	1x	217-225	PN 3312.5
HPW_0015	-0.2545	Chondrophore	NA	N29 E19	NE	1x	217-225	PN 3312.5
HPW_0016	0.9927	Chondrophore	NA	N29 E19	NE	2x	225-230	PN 3316.5
HPW_0017	0.3676	Chondrophore	NA	N29 E19	NE	2x	225-230	PN 3316.5
HPW_0018	0.2204	Chondrophore	NA	N29 E19	NE	2x	225-230	PN 3316.5
HPW_0019	0.7035	Chondrophore	NA	N29 E19	NE	3	230-235	PN 3320.5
HPW_0020	0.7345	Chondrophore	NA	N29 E19	NE	3	230-235	PN 3320.5
HPW_0021	0.0657	Chondrophore	NA	N29 E19	NE	3	230-235	PN 3320.5
HPW_0022	0.2459	Chondrophore	NA	N29 E19	NE	4	235-237.5	PN 3324.5
HPW_0023	-0.7769	Chondrophore	NA	N29 E19	NE	4	235-237.5	PN 3324.5
HPW_0024	0.4810	Chondrophore	NA	N29 E19	NE	4	235-237.5	PN 3324.5
HPW_0025	0.1163	Chondrophore	NA	N29 E19	NE	5	237.5-240	PN 3328.5
HPW_0026	0.1890	Chondrophore	NA	N29 E19	NE	5	237.5-240	PN 3328.5
HPW_0027	0.8110	Chondrophore	NA	N29 E19	NE	5	237.5-240	PN 3328.5

Table B2 continued

HPW_0028	0.3147	Chondrophore	NA	N29 E19	NE	6	240-242.5	PN 3333.5
HPW_0029	0.6378	Chondrophore	NA	N29 E19	NE	6	240-242.5	PN 3333.5
HPW_0030	0.8139	Chondrophore	NA	N29 E19	NE	6	240-242.5	PN 3333.5
HPW_0031	-0.4606	Chondrophore	NA	N29 E19	NE	7a	242.5-245	PN 3338a.5
HPW_0032	0.3778	Ventral Margin	NA	N29 E19	SE	6	240-242.5	PN 3335.51
HPW_0033	0.0831	Ventral Margin		N29 E19	NW	2x	225-230	PN 3315.51
HPW_0034	1.0306	Interannual Sequence	1	N29 E19	NW	2x	225-230	PN 3315.51
HPW_0035	-0.7414	Interannual Sequence	2	N29 E19	NW	2x	225-230	PN 3315.51
HPW_0036	-0.9539	Interannual Sequence	3	N29 E19	NW	2x	225-230	PN 3315.51
HPW_0037	-0.9506	Interannual Sequence	4	N29 E19	NW	2x	225-230	PN 3315.51
HPW_0038	-0.7573	Interannual Sequence	5	N29 E19	NW	2x	225-230	PN 3315.51
HPW_0039	0.4765	Interannual Sequence	6	N29 E19	NW	2x	225-230	PN 3315.51
HPW_0040	-0.2770	Interannual Sequence	7	N29 E19	NW	2x	225-230	PN 3315.51
HPW_0041	0.0335	Interannual Sequence	8	N29 E19	NW	2x	225-230	PN 3315.51
HPW_0042	0.3339	Ventral Margin	NA	N29 E19	NW	4	235-237.5	PN 3323.51
HPW_0043	-0.1157	Ventral Margin	NA	N29 E19	NW	4	235-237.5	PN 3323.51
HPW_0044	0.2085	Chondrophore	NA	N29 E19	SE	4	235-237.5	PN 3326.4
HPW_0045	-0.0504	Ventral Margin	NA	N29 E19	SE	4	235-237.5	PN 3326.4
HPW_0046	-0.8181	Interannual Sequence	1	N29 E19	SE	4	235-237.5	PN 3326.4
HPW_0047	0.9654	Interannual Sequence	2	N29 E19	SE	4	235-237.5	PN 3326.4
HPW_0048	-0.8191	Interannual Sequence	3	N29 E19	SE	4	235-237.5	PN 3326.4
HPW_0049	-0.1888	Interannual Sequence	4	N29 E19	SE	4	235-237.5	PN 3326.4
HPW_0050	0.0171	Interannual Sequence	5	N29 E19	SE	4	235-237.5	PN 3326.4
HPW_0051	-0.3625	Interannual Sequence	6	N29 E19	SE	4	235-237.5	PN 3326.4
HPW_0052	0.0537	Interannual Sequence	7	N29 E19	SE	4	235-237.5	PN 3326.4
HPW_0075	0.645	Interannual Sequence	1	N29 E19	SE	6	240-242.5	PN 3333.51
HPW_0076	0.3851	Interannual Sequence	2	N29 E19	SE	6	240-242.5	PN 3333.51
HPW_0077	0.5848	Interannual Sequence	3	N29 E19	SE	6	240-242.5	PN 3333.51
HPW_0078	0.3406	Interannual Sequence	4	N29 E19	SE	6	240-242.5	PN 3333.51
HPW_0079	0.4681	Interannual Sequence	5	N29 E19	SE	6	240-242.5	PN 3333.51
HPW_0080	0.6294	Interannual Sequence	6	N29 E19	SE	6	240-242.5	PN 3333.51
HPW_0081	0.0025	Interannual Sequence	7	N29 E19	SE	6	240-242.5	PN 3333.51

Table B2 continued

HPW_0082	0.8929	Interannual Sequence	8	N29 E19	SE	6	240-242.5	PN 3333.51
HPW_0083	1.0815	Chondrophore	NA	N29 E19	NE	7a	242.5-245	PN 3338.5a
HPW_0084	0.9899	Chondrophore	NA	N29 E19	NE	7a	242.5-245	PN 3338.5a
HPW_0053	0.4893	Ventral Margin	NA	N29 E19	SW	7	242.5-245	PN 3339.51
HPW_0054	-0.5739	Ventral Margin	NA	N29 E19	SW	8A	245-250	PN 3344A.51
HPW_0085	0.8112	Chondrophore	NA	N29 E19	NE	8a	245-250	PN 3343.5a
HPW_0086	0.7302	Chondrophore	NA	N29 E19	NE	8a	245-250	PN 3343.5a
HPW_0087	1.0762	Chondrophore	NA	N29 E19	NE	8a	245-250	PN 3343.5a

Table B2: Holmes Point West archaeological shell samples from N29 E19.

Site 62-8: unit N28 E21

Sample ID	$\delta^{18}O$ Value	Sample Location	Drill Increment	Unit	Quad	Level	Depth Below Datum (cm)	Catalog #
HPW_0088	1.2493	Chondrophore	NA	N28 E21	SE	1x	195-200	PN 3253.5
HPW_0089	0.6871	Chondrophore	NA	N28 E21	SE	1x	195-200	PN 3253.5
HPW_0090	1.1065	Chondrophore	NA	N28 E21	SE	2	200-205	PN 3257.5
HPW_0091	-0.1185	Chondrophore	NA	N28 E21	SE	2	200-205	PN 3257.5
HPW_0092	-0.0099	Chondrophore	NA	N28 E21	SE	2	200-205	PN 3257.5
HPW_0093	0.872	Ventral Margin	NA	N28 E21	SE	2	200-205	PN 3257.51
HPW_0094	-0.3843	Chondrophore	NA	N28 E21	SE	3	205-210	PN 3261.5
HPW_0095	0.4622	Chondrophore	NA	N28 E21	SE	3	205-210	PN 3261.5
HPW_0096	0.2171	Chondrophore	NA	N28 E21	SE	3	205-210	PN 3261.5
HPW_0097	-0.1181	Chondrophore	NA	N28 E21	SE	4	210-215	PN 3265.5
HPW_0098	0.1646	Chondrophore	NA	N28 E21	SE	4	210-215	PN 3265.5
HPW_0099	0.4573	Chondrophore	NA	N28 E21	SE	5	215-220	PN 3269.5
HPW_0100	0.1333	Chondrophore	NA	N28 E21	SE	5	215-221	PN 3269.5
HPW_0101	0.6062	Ventral Margin	NA	N28 E21	SE	5	215-221	PN 3269.51
HPW_0064	0.5314	Ventral Margin	NA	N28 E21	NE	4	210-215	PN 3263.2
HPW_0065	0.7080	Chondrophore	NA	N28 E21	NE	4	210-215	PN 3263.2
HPW_0066	0.1639	Ventral Margin	NA	N28 E21	NE	4	210-215	PN 3263.2
HPW_0067	0.6060	Ventral Margin	NA	N28 E21	NW	2	200-205	PN 3254.51
HPW_0068	-1.1848	Interannual Sequence	1	N28 E21	SE	5	215-221	PN 3269.51
HPW_0069	-1.3007	Interannual Sequence	2	N28 E21	SE	5	215-221	PN 3269.51

Table B3: Holmes Point West archaeological shell samples from N28 E21.

Site 62-8: unit N26 E18

Sample ID	$\delta^{18}O$ Value	Sample Location	Drill Increment	Unit	Quad	Level	Depth Below Datum (cm)	Catalog #
HPW_0055	0.1586	Chondrophore	NA	N26 E18	SE	3	230-235	PN 3426.5
HPW_0056	-0.1332	Chondrophore	NA	N26 E18	SE	3	230-235	PN 3426.5
HPW_0057	-0.1043	Chondrophore	NA	N26 E18	SE	3	230-235	PN 3426.5
HPW_0058	0.5219	Chondrophore	NA	N26 E18	SE	4	235-240	PN 3430.5
HPW_0059	-0.0463	Chondrophore	NA	N26 E18	SE	4	235-240	PN 3430.5
HPW_0060	-0.0074	Chondrophore	NA	N26 E18	SE	4	235-240	PN 3430.5
HPW_0061	-0.3458	Chondrophore	NA	N26 E18	SE	5A	240-245	PN 3434A.5
HPW_0062	0.1755	Chondrophore	NA	N26 E18	SE	5A	240-245	PN 3434A.5
HPW_0063	0.4818	Chondrophore	NA	N26 E18	SE	5A	240-245	PN 3434A.5

Table B4: Holmes Point West archaeological shell samples from N26 E18.

Site 62-8: unit N53 E30

Sample ID	$\delta^{18}O$ Value	Sample Location	Drill Increment	Unit	Quad	Level	Depth Below Datum (cm)	Catalog #
HPW_0001	0.4343	Chondrophore	NA	N53 E30	SW	3	240-245	PN 2363.5
HPW_0002	0.6733	Chondrophore	NA	N53 E30	SW	3	240-245	PN 2363.5
HPW_0003	1.5386	Chondrophore	NA	N53 E30	SW	3	240-245	PN 2363.5
HPW_0004	0.0988	Chondrophore	NA	N53 E30	SW	4	245-250	PN 2365.5
HPW_0005	0.5592	Chondrophore	NA	N53 E30	SW	4	245-250	PN 2365.5
HPW_0006	0.3551	Chondrophore	NA	N53 E30	SW	4	245-250	PN 2365.5
HPW_0007	0.5616	Chondrophore	NA	N53 E30	SW	5	250-255	PN 2367.5
HPW_0008	0.4539	Chondrophore	NA	N53 E30	SW	5	250-255	PN 2367.5
HPW_0009	0.4114	Chondrophore	NA	N53 E30	SW	5	250-255	PN 2367.5
HPW_0010	-0.0420	Chondrophore	NA	N53 E30	SW	6	255-260	PN 2369.5
HPW_0011	0.6218	Chondrophore	NA	N53 E30	SW	6	255-260	PN 2369.5
HPW_0012	0.4604	Chondrophore	NA	N53 E30	SW	6	255-260	PN 2369.5

Table B5: Holmes Point West archaeological shells sampled from N53 E30.

Site 44-13: units N77 E9 and N74 E11

Sample ID	$\delta^{18}O$ Value	Sample Location	Drill Increment	Unit	Column	Quad	Level	Below Datum (cm)	Catalog #
JCE_0001	0.5319	Chondrophore	NA	N77 E9	1	NE	1	0-5BD	PN 418
JCE_0002	1.2887	Chondrophore	NA	N77 E9	1	NE	1	0-5BD	PN 418
JCE_0003	0.9255	Chondrophore	NA	N77 E9	1	NE	1	0-5BD	PN 418
JCE_0004	0.6972	Chondrophore	NA	N77 E9	1	NE	5	22-25BD	PN 422
JCE_0005	1.0945	Chondrophore	NA	N77 E9	1	NE	5	22-25BD	PN 422
JCE_0006	1.4764	Chondrophore	NA	N77 E9	1	NE	5	22-25BD	PN 422
JCE_0007	-0.2204	Chondrophore	NA	N77 E9	1	NE	8	35-40BD	PN 425
JCE_0008	0.4846	Chondrophore	NA	N77 E9	1	NE	8	35-40BD	PN 425
JCE_0009	0.5499	Chondrophore	NA	N77 E9	1	NE	8	35-40BD	PN 425
JCE_0010	0.125	Interannual Sequence	1	N77 E9	1	NE	8	35-40BD	PN 425.1
JCE_0011	-0.1451	Interannual Sequence	2	N77 E9	1	NE	8	35-40BD	PN 425.1
JCE_0012	-0.1171	Interannual Sequence	3	N77 E9	1	NE	8	35-40BD	PN 425.1
JCE_0013	0.055	Interannual Sequence	4	N77 E9	1	NE	8	35-40BD	PN 425.1
JCE_0014	0.1918	Interannual Sequence	5	N77 E9	1	NE	8	35-40BD	PN 425.1
JCE_0015	0.4269	Interannual Sequence	6	N77 E9	1	NE	8	35-40BD	PN 425.1
JCE_0016	0.2182	Interannual Sequence	7	N77 E9	1	NE	8	35-40BD	PN 425.1
JCE_0017	0.585	Interannual Sequence	8	N77 E9	1	NE	8	35-40BD	PN 425.1
JCE_0018	0.4949	Ventral Margin	NA	N77 E9	1	NE	8	35-40BD	PN 425.1
JCE_0019	0.4803	Interannual Sequence	1	N77 E9	1	NE	5	22-25BD	PN 422.1
JCE_0020	0.531	Interannual Sequence	2	N77 E9	1	NE	5	22-25BD	PN 422.1
JCE_0021	0.0197	Interannual Sequence	3	N77 E9	1	NE	5	22-25BD	PN 422.1
JCE_0022	0.4012	Interannual Sequence	4	N77 E9	1	NE	5	22-25BD	PN 422.1
JCE_0023	0.5119	Interannual Sequence	5	N77 E9	1	NE	5	22-25BD	PN 422.1
JCE_0024	0.3106	Interannual Sequence	6	N77 E9	1	NE	5	22-25BD	PN 422.1
JCE_0025	0.4112	Interannual Sequence	7	N77 E9	1	NE	5	22-25BD	PN 422.1
JCE_0026	0.198	Interannual Sequence	8	N77 E9	1	NE	5	22-25BD	PN 422.1
JCE_0027	0.7286	Ventral Margin	NA	N77 E9	1	NE	5	22-25BD	PN 422.1
JCE_0028	0.5788	Chondrophore	NA	N74 E 11	2	NW	1	0-5cm	
JCE_0029	-0.1821	Chondrophore	NA	N74 E 11	2	NW	1	0-5cm	
JCE_0030	0.2961	Chondrophore	NA	N74 E 11	2	NW	1	0-5cm	
JCE_0031	0.2063	Chondrophore	NA	N74 E 11	2	NW	1	0-5cm	
JCE_0032	-0.5685	Chondrophore	NA	N74 E 11	2	NW	1	0-5cm	
JCE_0033	0.0771	Chondrophore	NA	N74 E 11	2	NW	1	0-5cm	
JCE_0034	0.5037	Chondrophore	NA	N74 E 11	2	NW	5	20-25	
JCE_0035	0.2172	Chondrophore	NA	N74 E 11	2	NW	5	20-25	
JCE_0036	-1.49	Chondrophore	NA	N74 E 11	2	NW	5	20-25	
JCE_0037	-0.2477	Chondrophore	NA	N74 E 11	2	NW	5	20-25	
JCE_0038	-0.2345	Chondrophore	NA	N74 E 11	2	NW	5	20-25	
JCE_0039	-1.6166	Chondrophore	NA	N74 E 11	2	NW	8	35-40	
JCE_0040	-0.0178	Chondrophore	NA	N74 E 11	2	NW	8	35-40	
JCE_0041	-0.1562	Chondrophore	NA	N74 E 11	2	NW	8	35-40	
JCE_0042	0.3864	Chondrophore	NA	N74 E 11	2	NW	8	35-40	

Table B6: Jones Cove archaeological shell samples from N77 E9 and N74 E11.

BIOGRAPHY OF THE AUTHOR

Emily Blackwood was born in Lewiston, Maine in 1992. A graduate of Edward Little High School, she earned a Bachelor of Arts in Anthropology and a minor in Earth Science from the University of Maine in December of 2015. The following Spring, she began her Master's research in the Quaternary and Climate Studies program at the University of Maine and Climate Change Institute with a focus in archaeology; in the Spring of 2019, she was accepted into and has begun her doctoral research in the Interdisciplinary Ph.D. program, also at the University of Maine. During her graduate career, Emily has held an assistantship through the Office of Equal Opportunity and the VEMI (Virtual Environment and Multimodal Interaction) Laboratory. She is a candidate for the Master of Science degree in Quaternary and Climate Studies from the University of Maine in August 2019.