

TAPHONOMIC INDICATORS OF DEAD OCEAN QUAHOG (*ARCTICA ISLANDICA*) SHELL AGE IN THE DEATH ASSEMBLAGE OF THE MID-ATLANTIC BIGHT CONTINENTAL SHELF

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ABSTRACT: Taphonomic indicators are often used to assess time-since-death of skeletal remains. These indicators frequently have limited accuracy, resulting in the reliance of other methodologies to age remains. *Arctica islandica*, commonly known as the ocean quahog, is a relatively widespread bivalve in the North Atlantic, with an extended lifespan that often exceeds two hundred years; hence, their shells are often studied to evaluate climate change over time. This report evaluates taphonomic age using 117 *A. islandica* shells collected from the Mid-Atlantic Bight offshore of the Delmarva Peninsula with radiocarbon dates extending from 60–4,400 cal years BP. These shells had varying degrees of taphonomic alteration produced by discoloration and degradation of periostracum. To determine if a relationship exists between taphonomic condition and time-since-death, radiocarbon ages were compared with the amount of remaining periostracum and type of discoloration. Old shells (individuals that died long ago) were discolored orange with no periostracum while younger shells (individuals that died more recently) had their original color, with some periostracum. Both the disappearance of periostracum and appearance of discoloration followed a logistic process, with 50% of shells devoid of periostracum and 50% discolored in about 1,000 years. The logistic form of long-term taphonomic processes degrading shell condition is first reported here, as are the longest time series for taphonomic processes in death assemblages within the Holocene record. This relationship can be utilized for triage when deciding what shells to age from time-averaged assemblages, permitting more efficient application of expensive methods of aging such as radiocarbon dating.

INTRODUCTION

Death assemblages are composed of skeletal remains representing the remnants of living communities spanning multiple years, a phenomenon known as time averaging (Flessa et al. 1993; Kowalewski 1996; Kidwell 1998, 2013; Butler et al. 2020). Exposure to the elements of the surrounding environment alters these skeletal remains, increasingly degrading them with time-since-death (Powell and Davies 1990; Walker 2001; Powell et al. 2011a). Increased length of exposure of the skeletal elements to taphonomic processes such as dissolution, abrasion, discoloration, and fragmentation should reflect increased time-since-death of the living organism (Butler et al. 2020). Determining if a shell is young (e.g., < 200 cal years BP) or old (> 200 cal years BP) can help identify the time period when an individual was alive. However, the age of a shell is often obscured by stratigraphic position due to time averaging within the death assemblage (Adomat et al. 2016; Rodrigues and Simões 2010; Powell et al. 1989; Powell et al. 1992; Butler et al. 2020). Powell and Davies (1990) document the rare case where physical condition of a bivalve shell provides information on time-since-death. Regrettably, a more common finding is that the taphonomic signature (sensu Davies et al. 1989; Staff and Powell 1990) of the skeletal remnant provides limited evidence of time-since-death, thereby restricting the ability to sort the temporal sequence of skeletal remains entering the death assemblage. Constraints to sorting the sequence of remains include the coarseness of the semiquantitative taphonomic metrics (Davies et al. 1990; Staff and Powell 1990; Powell et al. 2011a), the difference in taphonomic degradation for different species (Callender et al. 1994; Lockwood and Work

2006; Powell et al. 2011b), and varying taphonomic rates among environments of deposition (Best and Kidwell 2000; Powell et al. 2011a).

The limited reliability of taphonomic signature has resulted in a dependency on other means to determine time since death. Although a variety of options have been implemented (Szabo et al. 1981; Muhs and Kennedy 1985; Powell and Davies 1990; Powell et al. 1991), radiocarbon dating (e.g., Ritter et al. 2013; Kosnik et al. 2015; Adomat et al. 2016; LeClaire et al. 2022) and amino acid racemization dating (e.g., Kowalewski et al. 1998; Ortiz et al. 2005; Krause et al. 2010; Tomašových et al. 2014; Kosnik et al. 2015) have proven to be the most efficient methods to verify time-since-death. A determination of time-since-death is a critical component of studies designed to define the rate of taphonomic processes (Meldahl 1987; Meldahl et al. 1997), the extent of time averaging, (Kowalewski et al. 1998; Dominguez et al. 2016), and the clarification of the time history of community change consequent of anthropogenic processes (Bizjack et al. 2017) or climate change (MacIntyre et al. 1978; Powell et al. 2020). Accordingly, species' skeletal remains need to be aged using radiocarbon dating or amino acid racemization dating. Despite the value of studying death assemblage to address spatial and temporal changes in community composition, due to climate change or anthropogenic impact (Kidwell 2007; Negri et al. 2015; Bizjack et al. 2017; Arkle et al. 2018), such studies are limited because of the expense of dating large sample sizes (e.g., Butler et al. 2020). Having known indicators of shell age can help with shell selection for ¹⁴C dating and support ¹⁴C calibration of amino acid dating, particularly for geographically extensive datasets such as documented in

Powell et al. (2020), preventing a waste of funds on random, uninformed sample selection (Butler et al. 2020).

Arctica islandica is a remarkable species with a long lifespan, stenotypic temperature tolerance, and wide boreal distribution in the northern hemisphere, all characteristics that make this species an exceptional paleoclimatic indicator for the boreal province of the northern hemisphere (Dahlgren et al. 2000; Witbaard and Bergman 2003; Wanmaker et al. 2011; Hemeon et al. 2021). This clam's long lifespan (> 300 years) is distinctively valuable, recording paleoclimatic conditions for an extensive time period compared to shorter lived species. Unfortunately, the utilization of *A. islandica* shells as a paleoclimatic indicator over extended time periods is significantly limited by the need to determine time-since-death. In this study, shells from dead *Arctica islandica* were collected from the Mid-Atlantic Bight, offshore of the Delmarva Peninsula (LeClaire et al. 2022). Collected shells have radiocarbon dates spanning time from 60 to 4,400 cal years BP, documenting major transgressions and regressions of the species' range across the continental shelf. These dates coincide with warming and cooling climatic episodes and strongly suggest that this species might be used to track the dimensions of climate change throughout much of the North Atlantic Ocean and adjacent seas. Sample selection in LeClaire et al. (2022) would have been simplified if taphonomic signatures could be used to assess the age range of a specimen for future radiocarbon dating. The radiocarbon dated shells collected by LeClaire et al. (2022) vary in taphonomic condition with a range of remaining periostracum coverage and discoloration. An important question, then, is this: can time-since-death of *A. islandica* shells be distinguished using discoloration and periostracum condition? Answering this question would simultaneously also provide a rare estimate of taphonomic alternation of these shells as a function of interment time in the death assemblage.

Butler et al. (2020) asked a similar query when assessing the condition of several taphonomic characteristics, including the amount of remaining periostracum on *A. islandica* shells of various ages. Using discriminant analysis, Butler et al. (2020) found limited detectability in taphonomic changes needed to identify time-since-death of older shells, confirming that time-since-death can be difficult to determine from shell condition. Nevertheless, other studies have found evidence linking taphonomic indicators and the time spent in the death assemblage, including Powell and Davies (1990) who used shell color to categorize shells as young or old and long-term experimental deployments documenting time-dependent changes in taphonomic signature in a range of environments of deposition (Powell et al. 2011a). Local variability in the timing and types of taphonomic processes is likely an important reason for the different results between studies (e.g., Powell et al. 2011a, 2012). This study furthers these investigations using radiocarbon dates to determine if taphonomic condition, specifically shell color and condition of periostracum, of dead *A. islandica* shells from the Mid-Atlantic Bight continental shelf can be used to select specimens of varying times-since-death.

METHODS

Sample Collection

Shells of dead *A. islandica* were collected along the continental shelf with a 2.54-m wide hydraulic dredge on a commercial clam vessel, the *F/V Betty C*, offshore of the Delmarva Peninsula in August 2019 (Fig. 1). The vessel was a typical clam boat with a standard hydraulic dredge used throughout the *A. islandica* fishery with a penetration depth of approximately 20 cm (Parker 1971). The dredge was lined with 2.54-cm square wire on the bottom and knife shelf, and 2.54×5.08-cm rectangular wire on the sides, back, and door. The wire lining retained clam shells approximately ≥ 40 mm. Tows swept an area of approximately 118 m² with tow distance limited to prevent overfilling of the dredge. *Arctica islandica* shells were manually picked

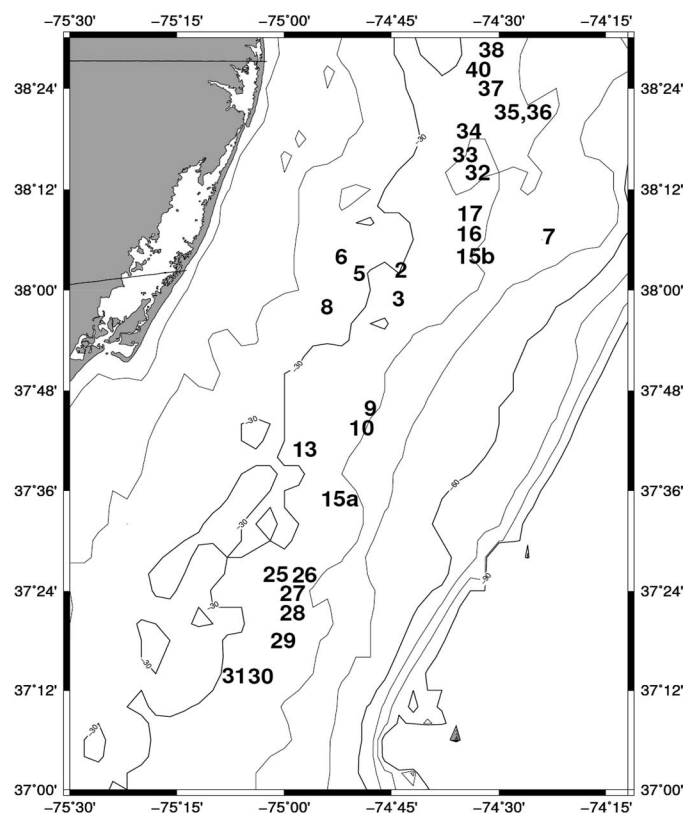


FIG. 1.—Map of stations where *Arctica islandica* were collected via dredge onboard the *F/V Betty C* in August 2019. LeClaire et al. (2022) include a table signifying the station from which each shell was collected. For context in a larger geographic region, see Figure 5 in Powell et al (2020). Bathymetric lines are in 10-m intervals from 10 to 90 m.

from the dredge haul as they were carried by a central conveyor belt. Following collection, all shells were archived until the start of this study.

Caveat Lector

Herein, the term age applies to the radiocarbon date obtained, not the age of the animal at death. The term time-since-death is often applied to this metric, but *A. islandica* is unusual in its long lifespan, so that many of the specimens have radiocarbon dates that include a substantial amount of elapsed time from birth to death. Because samples for dating were biased towards the oldest part of the shell, for many specimens, the radiocarbon date is more similar to time-since-birth than time-since death. To solve this inherent ambiguity, the terms time-since-death, time-since-birth, and age are synonymized, with the best denotation being time-since-birth. The term age when applied should be clearly distinguished from lifespan, the elapsed time between birth and death.

The analyses reported are designed to reveal the rate of taphonomic degradation of the shell. This is distinctive to the rate of time averaging (the mixing of shells of differing age) and to the rate of shell loss (a measure of shell disappearance from the death assemblage). Historically, the sampled region has been fished by the Atlantic surfclam fishery, using hydraulic dredges. The coverage of bottom contact by this fishery is small in comparison to the geographic extent of this study (see NEFSC 2017); nonetheless, some mixing of the upper 20 cm may have occurred at some sites due to the fishery. Consequently, the data presented should not be considered an inference of a rate of time averaging in these surficial sediments. However, this mixing does not compromise the analyses herein which focus on the relationship of shell age and taphonomic condition. The

smaller number of old shells does likely imply a continued rate of shell loss over the thousands of years encompassed by the dataset; despite this implication the rate of shell loss cannot be ascertained.

Finally, the shells were obtained from a large number of sites to assure a geographically expansive collection, but the ages of shells are not randomly distributed amongst sites; neither are the taphonomic characteristics. The number of radiocarbon ages is insufficient to discriminate differences in taphonomic alteration as a function of age between locales. As a consequence, the dataset is analyzed comprehensively to identify temporal changes over the geographically expansive collection area.

Shell Imaging

A total of 117 dead shells were selected from the archive to include a variety of sizes, colors, and collection sites and retained for further investigation in this study (see also LeClaire et al. 2022). As *A. islandica* is an equivalence species, both left and right valves were used indiscriminately in this study. All dead shells were disarticulated when collected. Internal and external sides of each shell were photographed to capture the exterior condition of the valve before cutting the valve for radiocarbon dating (Fig. 2). Color swatches in the Munsell Book of Color (Munsell Color 2010) were matched to the colors present on the shell and included in the image for comparison (Fig. 2). Dominant shell color was determined while photographing the valve and recorded for further analysis.

Radiocarbon Dating

Once shells were imaged, the valves were covered in clay to prevent shattering and cut along the axis of growth using a wet tile saw. Cutting into the valve allows access to carbonate uncontaminated by bionts and the surrounding environment. The cut edge of one half of the valve was then ground using 240 grit silicon carbide abrasive paper to remove any clay contaminants. Using a Dremel tool, shell powder samples were extracted from the cut edge of the ground valve half near the hinge and umbo. Consequently, the sample came from the part of the shell deposited during the early years of life. The resulting shell powder samples (> 10 mg) from all samples were sent to the W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California, Irvine for analysis. Radiocarbon ages of samples will be denoted hereafter as ages that approximate the elapsed time between the time of collection and the time since birth of the *A. islandica* (LeClaire et al. 2022).

Date Calibration

Radiocarbon ages ($\pm$ 15–25 years depending on the sample) were calibrated using the Marine13 reservoir age of 400 years (Reimer et al. 2013). Off the Delmarva Peninsula, *A. islandica* live in the Cold Pool, a cold-water near-bottom water mass trapped by thermal stratification during the summer on the outer continental shelf. The Cold Pool derives water in varying proportions from Arctic and North Atlantic sources depending on the year (Miles et al. 2015; Wang et al. 2019; Chen and Curchitser 2020; Chen et al. 2021), providing some uncertainty in this correction factor considering the marine reservoir effect differs both temporally and spatially (Alves et al. 2003; Heaton et al. 2020). Given the absence of a regional marine reservoir age correction for the Mid-Atlantic Bight offshore continental shelf, live *A. islandica* were collected off New Jersey, Long Island, and Georges Bank as described by Hemeon et al. (2021, 2023) and Sower et al. (2023). These live animals were shucked and their shells aged and radiocarbon dated. A correction factor of 400 years was confirmed based on the comparison between the radiocarbon birth year and the visual birth year obtained by counting the annual growth lines (LeClaire et al. 2022). The residual median when comparing the two aging methods was $\sim$ 5 year, a mean of $\sim$ 7 year, and a standard deviation of $\pm$ 38.67 year.

More research is needed to further constrain the potential error when calibrating marine carbon dates in this region over a long time period, during which the Cold Pool likely varied in intensity. Nonetheless, the radiocarbon ages obtained in this study were corrected assuming that bottom water conditions during the lifetime of the sampled shells were consistent with the Marine13 marine reservoir age.

Five dead *A. islandica* shells were alive after 1950; hence, they were exposed to bomb produced carbon-14 from the atmospheric detonation of the atomic bombs. To estimate radiocarbon birth year post-1950, a reference time series of $\Delta^{14}\text{C}$ (% deviation of the sample from the radiocarbon standard defined by Stuiver and Polach 1977) determined by Kilada et al. (2007) was applied (see also Scourse et al. 2012).

Taphonomic Evaluation

The taphonomic condition of shells was assessed using images taken prior to processing for radiocarbon dating. Taphonomic condition was assessed using two criteria: discoloration and the amount of remaining periostracum. Dissolution was excluded from analysis despite shell surfaces showing evidence of dissolution, because the degree of dissolution was not easily quantified. *Arctica islandica* is relatively resistant to dissolution (Powell et al. 2011b) and evidence of endobionts is very rare. Epibionts were not observed. The degree of periostracum loss was assessed by dividing the shell surface into a series of standard shell areas, as used in Staff and Powell (1990) and Brett et al. (2011) (Powell 2020, fig. 1), and then visually estimating and recording the percent periostracum for each shell area (see Brett et al. 2011 for an example of this type of analysis and Smrecak and Brandt 2017 for methodological comparisons). A value for the entire valve was taken as the area-weighted average of the individual area values. Periostracum coverage percentages were arcsine square-root transformed (Sokal and Rolf 1998) to conduct a one-way ANOVA. Shells were also allocated into two simple categories: periostracum present (1) or absent (0) as has historically been done (e.g., Powell et al. 2011a) (Fig. 2).

The coloration of each shell was matched to color swatches from the Munsell Book of Color (Munsell Color 2010). Using the most prevalent swatches, the dominant color on each shell was recorded, and discoloration from the original shell color (white) was characterized as present (1) or absent (0) (Fig. 3).

As the probabilities of a shell having complete periostracal coverage or original color at age asymptoted to 100% and 0%, logistic regressions were run using the statistical package in R (R Core Team 2022) to determine the probability at age of a dead shell having periostracum and discoloration present. The dataset was sufficiently sparse as to limit the application of this technique to the observed types of discoloration, hence the focus on the presence or absence of any type of discoloration.

RESULTS

Periostracum

The radiocarbon dates and taphonomic condition of 117 dead *A. islandica* shells were compared. Radiocarbon dates for the 117 sampled shells ranged from 61–4,392 cal years BP. LeClaire et al. (2022, fig. 3) provide details of the dispersion of shell ages through this time period. Sixty-seven of the total 117 shells were dated < 300 yr cal BP. The remaining 50 shells were much older, with dates exceeding 500 years cal BP. Taphonomic condition of shells was widely dispersed ranging from almost 100% periostracum intact to no periostracum remaining (Fig. 4). Seventy-one shells had some degree of periostracum remaining. Sixty-three of the shells with periostracum were radiocarbon dated between 67–300 cal years BP (Fig. 4). Eight shells were born in the 800s cal years BP, and the 1200s cal years BP (Fig. 5). However, shells born between 858–1,223 cal years BP retaining periostracum had less than 16% of the original periostracum remaining on the shell surface (Fig. 4). A one-way ANOVA



FIG. 2.—Images showing shells with varying levels of periostracum coverage. **A)** The first shell on the left has almost all periostracum intact. **B)** The middle photo depicts a shell with some (48%) periostracum remaining. **C)** The exact percentage was estimated using the methods from Staff and Powell (1990). The image on the right depicts a shell with no remaining periostracum. Shell A, B, and C are 96.12mm, 89.68mm, and 83.55 mm in length, respectively. Length encompasses the distance from the anterior to posterior edge.

was conducted on the shells with periostracum present to evaluate the relationship between the percent periostracum coverage relative to radiocarbon age. The relationship between coverage and age was statistically significant ($F = 27.88$, d.f. = 70, $p = 1.46\text{e-}06$).

The probability of periostracum being present decreased in a logistic fashion with time-since-death. A logistic curve (Eq. 1) fit to the probability of the presence of any remaining periostracum on a shell of a given radiocarbon age between 0–4,000 years cal BP (Fig. 5) yielded the following equation:

$$P = \frac{e^{3.2406 - 0.0028x}}{1 + e^{3.2406 - 0.0028x}} \quad (\text{Eq. 1})$$

where P is the probability of finding intact periostracum and x is cal years BP. The midpoint ($p = 0.5$) occurs at 1,157 cal years BP. The 10% and 90% probability values are 1,942 cal years BP and 372 cal years BP, respectively. Thus, the majority of shells lose all periostracum over a ~ 2,000-year time period with a substantial portion of this loss occurring during their extended lifespan of greater than 200 years. The 90% value is near the oldest animal so far found living in the Mid-Atlantic region of 310 years (Hemeon et al. 2021) and the variability in percent periostracum retention is substantial in this time period (Fig. 4). The loss of this layer is expected for animals with a long lifespan as periostracum is routinely lost, during a period of 200–300 years, due to erosion from the umbo down. Therefore, a substantial portion of measured periostracum loss in the first 300 years likely occurred while the animal was alive rather than dead.

Discoloration

Shell coloration was grouped into five main categories: white, orange, white-orange, orange-blue-gray, and white-gray (Fig. 3). These dominant categories were determined using the color swatches that were matched to the coloration of each shell. White was deemed the original condition of the shell with all other categories being a variation of shell discoloration. The samples included 64 white shells, 37 orange shells, nine white-orange shells, five orange-blue-gray shells, and two white-gray shells. Over half of the sampled shells retained the original, white shell color. The distribution of shell colors over time is shown in Figure 6. Note the biased distribution of white shells in the first 300 years cal BP and orange shells in shells aged > 2,000 years cal BP.

Of the shells that were discolored, the majority were orange. Orange shells were collected at a wide range of stations and represented a wide range of radiocarbon ages. Logistic regression was used to analyze the

relationship between radiocarbon age and orange shell discoloration. In contrast to gray discoloration discussed subsequently, orange discoloration did bear a significant relationship with time-since-death ($P < 0.001$) (Fig. 6). Normally the entire shell surface was discolored orange. The great majority of the orange-discolored shells dated to > 302 cal years BP. A logistic curve (Eq. 2) was fit to the probability of discoloration (Fig. 6) and a given radiocarbon age between 0–4,000 years cal BP (Fig. 7):

$$P = \frac{e^{-2.088 + 0.0021x}}{1 + e^{-2.088 + 0.0021x}} \quad (\text{Eq. 2})$$

where P is the probability of discoloration and x is cal years BP. The midpoint ($p = 0.50$) occurred at 994 cal years BP. The 20th percentile occurred at 334 cal years BP, in the time frame of the oldest *A. islandica* collected living in the Mid-Atlantic region (310 yr; Hemeon et al. 2021). Most (90%) of shells were discolored by 2,040 cal years BP.

Of the remaining discolored shells, five shells were classified as orange-blue-gray, with one shell radiocarbon dated at 2,017 cal years BP and the remaining four between 3,427–3,467 cal years BP of age (Fig. 6). The two shells deemed as white-gray were both aged at 1,187 cal years BP. Shells exhibiting variations of gray discoloration were sufficiently rare that all categories including that color were incorporated under the color gray for further analysis. These shells featuring gray discoloration were all > 1000 cal years BP, suggesting that gray discoloration is an indicator of an older shell. However, a logistic regression showed that a significant relationship did not exist between time-since-death and the occurrence of gray discoloration, in accordance with expectation, given the presence of gray-discolored shells in the middle of the shell age range (Fig. 6). However, the limited geographic distribution of the sample collection sites (only three of the total 25 stations) yielding these shells does not permit the further inference that gray discoloration was an intermediate taphonomic state.

DISCUSSION

Endobiont traces were rare and epibionts were never observed, suggesting that these shells remained exposed at the sediment surface after death for only a brief time (for examples of colonization with increased surface exposure, see Lescinsky et al. 2002; Brett et al. 2011; Rodland et al. 2014; Paga-Bernabéu and Aquirre 2017). Parsons-Hubbard et al. (1999) noted that any sediment, even a dusting, can severely limit epibiont colonization. Hence, the processes of periostracum degradation and discoloration are those that took place for shells buried beneath the sediment surface, but no deeper than the sampling depth of the hydraulic

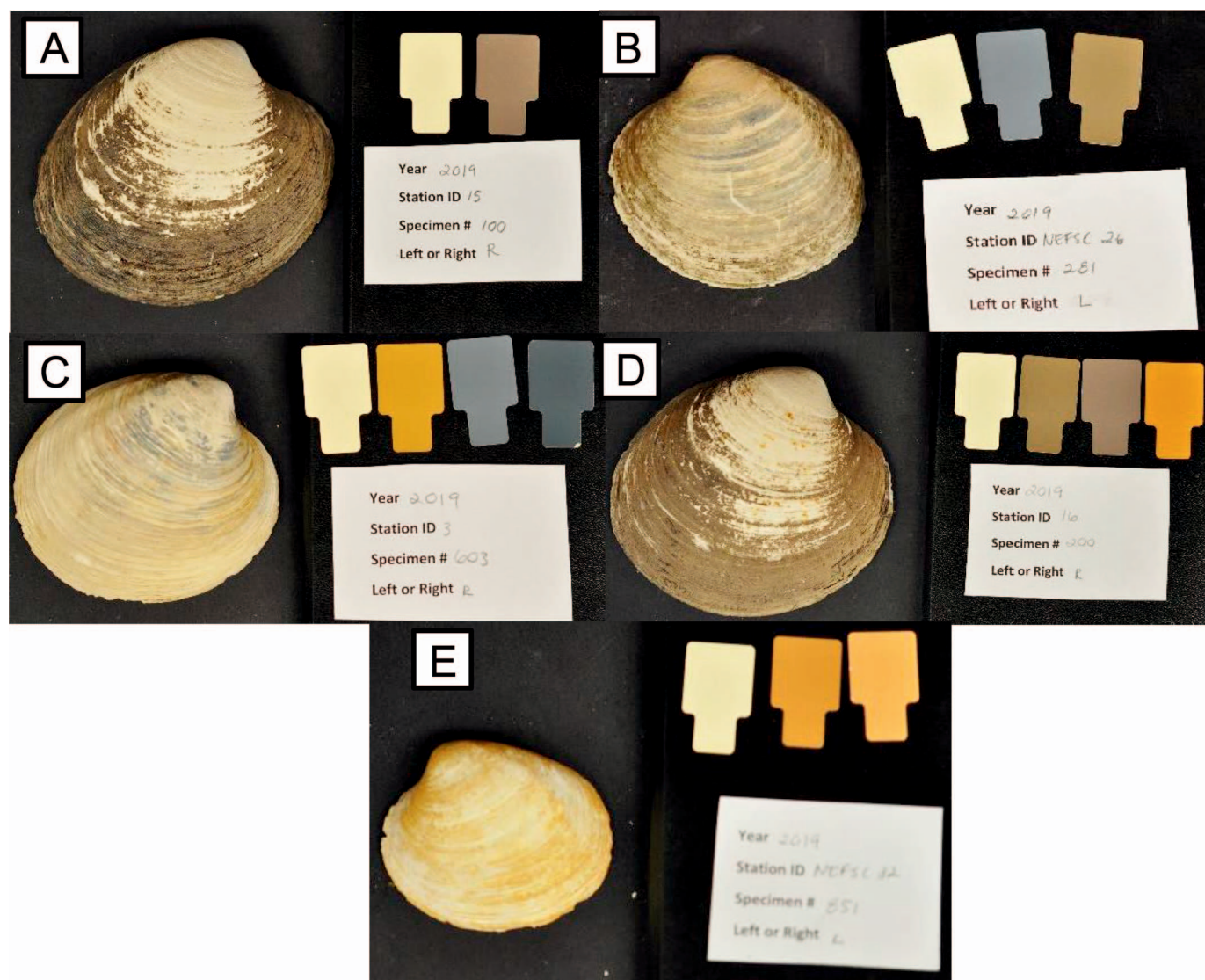


FIG. 3.—Images showing the original color of shells. **A)** White and the four variations of discoloration that were seen in the collected samples. **B)** White-gray. **C)** Orange-blue-gray. **D)** White-orange. **E)** Orange. Color swatches are from the Munsell Book of Color (A) N 2.5Y 9/2, 5YR 5/1; (B) 2.5Y 9/2, 10B 5/2, 10YR 5/2; (C) 2.5Y 9/2, 10YR 6/6, 10B 5/2, 10B 4/2; (D) 2.5 YR 9/2, 10YR 8/2, 5 YR 5/1, 7.5YR 6/8; (E) 2.5Y 9/2, 7.5 YR 6/6, 7.5YR 7/6). Handwritten specimen cards detail the year the sample was collected, the station ID, specimen ID#, and right or left value used. All shells were collected in 2019. Shell A was from station 15, specimen ID 100, and a right valve. Shell B was from station 26, specimen ID 281, and a left valve. Shell C was from station 3, specimen ID 603 and a right valve. Shell D was from station 16, specimen ID 200 and a right valve. Shell E was from station 22, specimen #851 and a left valve. Shell lengths: A = 103.2 mm; B = 76.08 mm; C = 82.71 mm; D = 101.24 mm; E = 69.31 mm.

dredge (~ 20 cm). *Arctica islandica* has short siphons and thus spends much of its life buried, but near the sediment-water interface. Observations of living *A. islandica* show that some periostracal deterioration occurs during their extended lifespan, however, likely due to erosion during periodic deeper burrowing which is an important behavioral adaptation of this species (Taylor 1976; Strahl et al. 2011). Nonetheless, the retrieval of the sampled shells by hydraulic dredge shows that even the oldest shells remained near the sediment surface, supporting the notion that near-surface biological and geochemical processes were responsible for the primary taphonomic outcomes.

Discoloration is rarely an important taphonomic characteristic for fossil shells, but its application to the taphonomic signature of death assemblages has received wide attribution (e.g., Frey and Howard 1986; Powell and Davies 1990; James et al. 2005; Powell et al. 2011a, 2012). Discoloration of the shell is most likely a result of the chemistry of the surrounding

environment in which dead shells were retained. Colors as wide ranging as brown, green, orange, gray, and black have been noted, some of them commonly and some definitively associated with certain environments of deposition (e.g., Cutler 1995; Lazo 2004; Rodrigues and Simões 2010; Powell et al. 2011a, 2012).

Orange discoloration was the most dominant form of discoloration in our dataset, especially on older shells; however, orange discoloration is rarely noted on specimen remains in other studies (i.e., Lazo 2004; James et al. 2005; Best 2008; Powell et al. 2011a). The orange color may be a result of iron oxidation, a common process on the seafloor and a potential explanation for the limited appearance of gray discoloration, with the oxidized mineral product forming orange and yellow pigments (Powell et al. 2008). In species like *Mercenaria mercenaria*, pyrite is incorporated into the shell (Clark and Lutz 1980) and can result in orange discoloration after oxidation (Powell et al. 2008). Exposure to seawater for extended

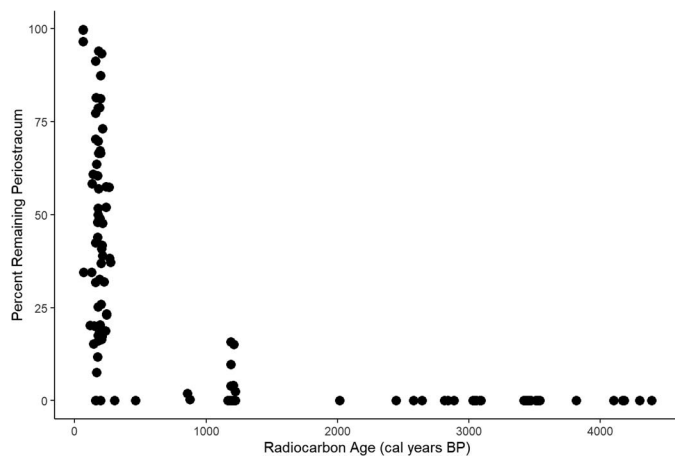


FIG. 4.—Estimated percent of remaining periostracum compared to the radiocarbon age of the shell sample.

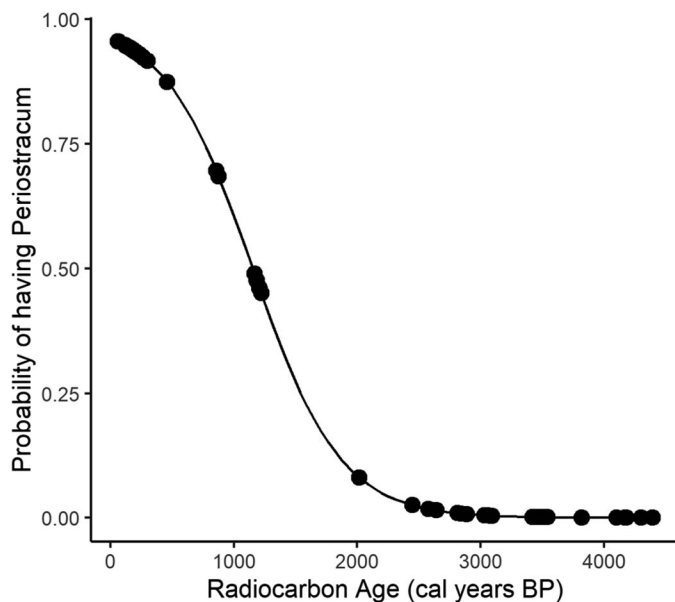


FIG. 5.—Logistic curve showing the probability of a dead *Arctica islandica* shell of a known radiocarbon age having any periostracum remaining on the external shell surface. Black dots show the probability associated with each age of a shell recorded in Table 1.

periods of time can result in sulfide infusion into the shell forming iron sulfide (see later discussion) and pyritization on the shell surface, either of which might support a subsequent chemical change in the shell due to direct oxidation or microbial production (Powell et al. 2008). In the present case, importantly, the orange discoloration was not a product of contact with oxygen during sample retrieval. These shells were discolored orange *in situ*, thus a diagenetic process is required. Products of iron sulfide and pyrite oxidation include a variety of iron oxy-hydroxides varying in color from yellow to orange to red, including the minerals schwertmannite and goethite, characterized by an orange pigment (Edwards et al. 2004; Omoregie et al. 2008; Li et al. 2011; Batta et al. 2013; Mitsunobu et al. 2021). The distribution of this form of discoloration across the sample region suggests a widespread geochemical process on the Mid-Atlantic Bight continental shelf emphasizing the oxidation of iron compounds resulting in a long-term stable discoloring process.

Gray to black discoloration is one of the most common shades of discoloration (MacIntyre et al. 1978; Frey and Howard 1986; Pilkey and Curran 1986; Thielert et al. 2001; Walker 2001; Best 2008; Powell et al. 2011a) and normally is the result of exposure to hydrogen sulfide. The shells that contained gray discoloration were found at three of the 25 stations sampled. This local occurrence may indicate a specific difference in the habitat surrounding the death assemblage at these stations; however, three stations with gray shells, also featured shells with orange discoloration. Furthermore, few samples collected were gray (seven gray shells out of 53 discolored shells), with the dominant discoloration in this study being orange, suggesting that the gray endpoint of discoloration is not an important process on this region of the continental shelf.

Comparing the calibrated radiocarbon ages of shells to the taphonomic condition revealed that older shells usually had no remaining periostracum and normally were characterized by discoloration. Almost always this discoloration was an orange pigmentation. The generality of this condition is particularly remarkable when considering the retrieval of these shells over most of the sampled region which includes almost 1.5 degrees of latitude (LeClaire et al. 2022). Such a wide range of taphonomic similarity is not routinely recorded (e.g., Tanabe and Arimura 1987; Best and Kidwell 2000; Powell et al. 2011a). Increasing time-since-death increases the probability of discoloration and loss of periostracum (Figs. 4–7), but the trend is substantially both nonlinear and non-exponential, strongly suggesting a profoundly different time dependency in the rate compared to previous analyses of taphonomic processes and time averaging (Powell et al. 1986; Powell et al. 2006; Krause et al. 2010; Powell et al. 2011a; Tomašových et al. 2014). Figure 7 shows that the probability of a shell being discolored increases along a logistic curve as the radiocarbon age increases, with dead shells older than 2,500 years having a higher probability of being discolored compared to younger shells. Additionally, the probability of dead shells maintaining periostracum decreases as radiocarbon age increases (Fig. 5). Dead shells older than 2,500 years have a 0% chance of having any periostracum remaining on the exterior surface of the shell (Fig. 5).

Similar to Powell and Davies (1990), our results depict a clear relationship between the discoloration of a shell and a longer time-since-death. The presence of periostracum is also an indicator of time-since-death, with periostracum absent on all old (< 1300 cal years BP) shells. These findings differ from recent studies, such as Butler et al. (2020) who determined that old, dead *A. islandica* shells collected from Fladen Ground in the North Sea have no discernable taphonomic characteristics, including remaining periostracum, to help identify time-since-death. However, Butler et al. (2020) infers that this may be an aspect of the local shelf environment in which the dead shells are retained. Limited research into the condition of periostracum after death for most bivalve species and study locations impedes the application of our results to other bivalves from a broader geographic area. Although considerable information exists about the breakdown of the organic matrix in a shell after death (e.g., Kimber and Griffin 1987; Powell et al. 1989; Powell et al. 1991; Mitchell and Curry 1997; Clark 1999), the process of periostracum decay is poorly studied (Poulicek et al. 1981; Poulicek and Jeuniaux 1982) though bacterial attack would seem to be of potential importance (Dungan et al. 1989; Paillard et al. 2004).

Additionally, the timescale of interest will influence how effective discoloration and presence of periostracum are to distinguishing between age cohorts. The difficulty of discerning between young and old shells increases on smaller time scales, such as comparing a 100-year-old shell and a 1,000-year-old shell. Nonetheless, the scale of time observed is consistent with the scale of time averaging in some assemblages (Carroll et al. 2003; Kosnik et al. 2009; Dexter et al. 2014; Ritter et al. 2017). Time averaging has been modeled as an exponential process (Carroll et al. 2003; Kosnik et al. 2009; Tomašových et al. 2014), but taphonomic

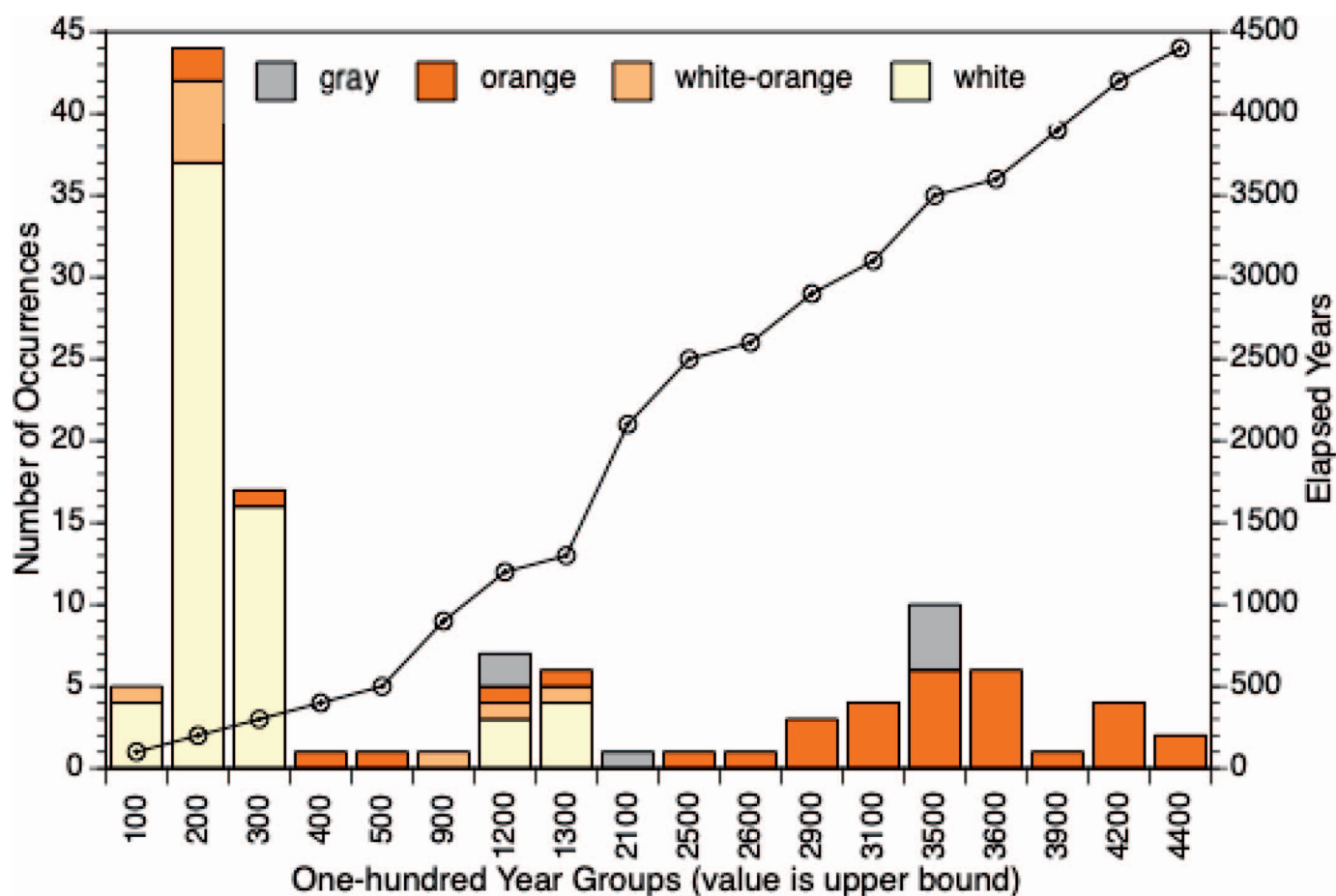


FIG. 6.—Distribution of shell color by age, in century intervals. Age shown is the upper bound of that century. Nonlinearity in elapsed time trend (right y axis) indicates missing centuries.

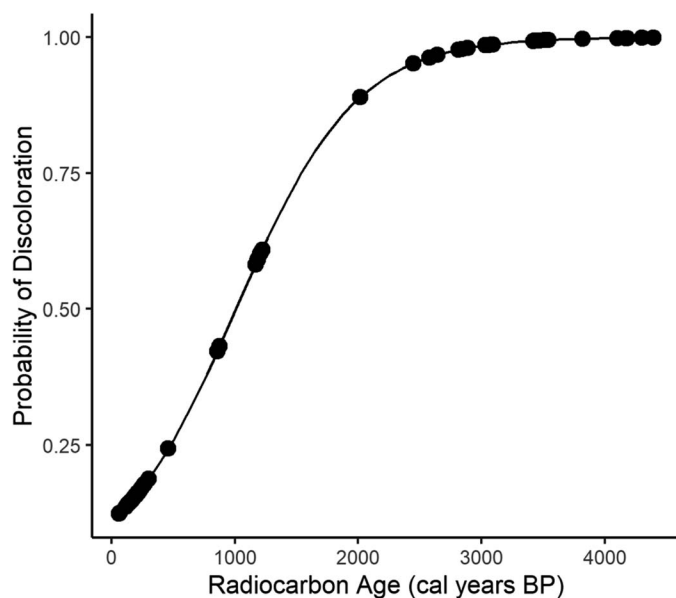


FIG. 7.—Logistic curve showing the probability of a dead *Arctica islandica* shell of a known radiocarbon age being discolored. Black dots show the probability associated with each age of a shell recorded in Table 1.

processes frequently do not follow a similar time trajectory (e.g., Powell et al. 2011a). In this study, the decline of periostracum coverage and increase in discoloration followed a logistic process. For periostracum, loss begins during life, progressing at a low rate for a time (Fig. 4) followed by a rapid change in taphonomic degradation rate after about 500 yr. The probability of having periostracum is $\sim 90\%$ at 500 years, $\sim 10\%$ at 2000 years, and thereafter, none remains (Fig. 5). The initiation of a rapid decline in coverage is similar to the oldest living *A. islandica* collected, suggesting that *A. islandica* shells begin to degrade rapidly on a time scale similar to the species' lifespan. Discoloration, on the other hand, begins in earnest long after death, indicating a requirement for long-term burial to initiate the process. The entire time trajectory of periostracum degradation and discoloration is similar to rapidly changing rates of certain taphonomic processes reported by Powell et al. (2011a), being highly nonlinear and clearly non-exponential, though the time scale is very different, and suggests that rapid and highly non-linear time-dependent changes in taphonomic rates are likely a normal condition.

CONCLUSIONS

To assess the potential for taphonomic condition as an indicator of time-since-death, this study utilized the dead shells of the long lived bivalve *Arctica islandica* to evaluate whether old shells could be visually identified. Such an option would greatly improve the ability to trace range shifts over Holocene time on the continental shelf as this method could be

TABLE 1.—Table depicts the location and taphonomic condition of each sample. The location of station numbers are shown in Figure 1. Each radiocarbon age is representative of one shell with associated color and periostracum coverage in the following columns listed respectively.

Station number	Radiocarbon age (yr cal BP)	Dominant shell color	Percent periostracum coverage
2	192, 207	white, white	48.9, 41.7
3	3427, 3452, 3462, 3460	orange-blue-gray, orange-blue-gray, orange-blue-gray, orange-blue, gray	0, 0, 0, 0
5	237	white	51.95
7	272, 2643, 2843, 2888, 3093, 3468, 3542, 3817	white, orange, orange, orange, orange, orange, orange, orange	37.2, 0, 0, 0, 0, 0, 0, 0
8	61, 62, 62, 63	white, white, white, white	99.7, 96.55, 99.55, 99.55
9	243, 263, 302, 2813, 3083, 3418, 4182	white, white, orange, orange, orange, orange, orange	23.3, 38.2, 0, 0, 0, 0, 0
10	3032, 3047, 3057	orange, orange, orange	0, 0, 0
13	3472	orange	0
15a	172, 177, 177, 177, 182, 182, 198, 262, 4302	white, white, white, white, white-orange, white, white, white, orange	48, 51.75, 69.75, 78.65, 19.3, 66.45, 36.85, 57.37, 0
15b	128, 132, 158, 172, 212, 4392	white, white, white, white, orange, orange	34.44, 58.25, 0, 11.7, 38.95, 0
16	157, 157, 177, 182, 188, 193, 197, 198, 203, 212, 222, 3517, 4102	white, white, white, white, white, white, white-orange, white, white, white, white, orange, orange	42.4, 77.3, 17.55, 48.5, 32.6, 67.2, 66.5, 25.9, 40.8, 73.05, 31.95, 0, 0
17	167, 171, 177, 177	white, white, white, white	7.58, 43.95, 16, 25.25
25	162, 167, 197, 2447	white, white, orange, orange	81.45, 63.5, 0, 0
26	182, 858, 1168, 1183, 1187, 1187, 1187, 1188, 1208, 1212, 1223	white, white-orange, white, white, white-orange, white-gray, white-gray, orange, white, orange, white	56.95, 2, 0, 0, 3.95, 9.75, 15.75, 0, 4.1, 15.05, 2.5
27	157, 162, 1167, 1207, 1223, 2578	white, orange, white, white, white, orange	91.2, 0, 0, 0, 0, 0
28	65, 197, 232, 242, 462	white-orange, white, white, white, orange	34.5, 87.3, 18.75, 23.05, 0
29	177, 182, 197, 237	white-orange, white, white, white	na, 94, 81.1, 57.45
30	2017, 3512, 3512, 3532	orange-blue-gray, orange, orange, orange	0, 0, 0, 0
31	162, 172, 187, 207, 877	white, white, white, white, white-orange	20, 60.5, 78.72, 17.3, 0.3
32	3437, 3447, 3472, 3527	orange, orange, orange, orange	0, 0, 0, 0
33	212	white	47.7
34	117, 137, 147	white-orange, white, white	20.2, 60.8, 20.05
35	157, 157, 192	white, white, white-orange	31.8, 70.2, 20.4
38	142, 202, 202	white, white, white	15.2, 16.4, 93.32
40	4172, 4182	orange, orange	0, 0

used to inform sample selection when choosing which specimens to date and retain for further analyses. Data presented here support the use of taphonomic signatures to increase radiocarbon and racemization dating efficiency for studies, such as LeClaire et al. (2022), in which a wide range of shells of differing age were collected at a sample site. Such studies include sclerochronology and the use of death assemblages to track range shifts and environmental conditions over long time periods and large geographic scales. Conservation paleobiology research, exploring the use of long-lived bivalves as paleoclimatic indicators, would also significantly benefit from reliable taphonomic indicators used to determine time-since-death. A need for further research still exists to determine the chemical processes behind the discoloration of these shells and its relation to time-since-death and the processes controlling decay of the periostracum, which happens on a time scale distinctly shorter than that of discoloration. Both processes follow a logistic model, suggesting that taphonomic degradation is highly nonlinear in time. The logistic nature of the process does provide an important dichotomy permitting efficient sorting of shells into relatively young and relatively old age groups. Whether other taphonomic processes might impose a similar dichotomy given a sufficiently long period of observation remains unexplored.

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