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Invited Research Papers

Is there a reliable taphonomic clock in the temperate North Atlantic? An example from a North Sea population of the mollusc *Arctica islandica*

Paul G. Butler[a,*], Nicole M. Fraser[b], James D. Scourse[a], Christopher A. Richardson[c], Charlotte Bryant[d], Jan Heinemeier[e]

[a] *Centre for Geography and Environmental Sciences, College of Life and Environmental Sciences, University of Exeter, Penryn, Cornwall, TR10 9EZ, UK*
[b] *École Internationale de Genève - La Châtagneraie Chemin de la Ferme 2, 1297 Founex, Switzerland*
[c] *School of Ocean Sciences, College of Environmental Sciences and Engineering, Bangor University, Menai Bridge, Anglesey, LL59 5AB, UK*
[d] *NERC Radiocarbon Facility, Scottish Universities Environmental Research Centre, University of Glasgow, Rankine Avenue, East Kilbride, Scotland, G75 OQF, UK*
[e] *Department of Physics and Astronomy, University of Aarhus, Ny Munkegade 120, Building 1525, DK-8000 Aarhus C, Denmark*

A R T I C L E I N F O

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A B S T R A C T

Two hundred and seventy-seven shells of the long-lived bivalve mollusc *Arctica islandica*, collected from the Fladen Ground, northern North Sea, were radiocarbon dated and their taphonomic condition assessed, in order to determine whether taphonomic condition might provide a reliable indication of time since the death of the animal. With nine stations from across the Fladen Ground sampled, some strong geographic biases in ^{14}C ages were apparent, with living and modern (post-bomb pulse) material found in the northern part of the Fladen Ground while older material (first half of the last millennium and Early Holocene/Lateglacial) was concentrated in the central and western sites. Samples from the south and east Fladen Ground were sparse and were dominated by material from the second half of the last millennium. This south-north distribution is interpreted as the result of environmental change over millennial time-scales in the North Sea causing a gradual northward shift of living *A. islandica* populations and is not thought to be related to *post mortem* transport of shells to the south and east. Taphonomic condition, assessed using discriminant analysis and principal component analysis of five characteristics (amount of remaining periostracum, presence and condition of the ligament, extent of erosion at the shell margin, amount of bioerosion, and nacre condition), appeared to be a generally unreliable indicator of time since the death of the animal. Based on these five taphonomic characteristics, discriminant analysis placed 81.1% of post-bomb shells, 39.6% of shells from the period 0–500 yr BP, 68.0% of shells from the period 500–1000 yr BP and 20.0% of shells from the Early Holocene/Lateglacial group into the correct radiocarbon age grouping, providing no support for the idea that this method can be used to triage shells for chronology construction as an alternative to radiometric dating.

1. Introduction

Time-averaging, the mixing of biotic remains of different ages into a single accumulation, is a well-known and usually unavoidable property of fossil assemblages (Flessa et al., 1993; Kowalewski, 1996; Kidwell, 1998, 2013). In a seabed environment, it can result from bioturbation (churning of sediment by burrowing organisms), physical hydrodynamic processes (resuspension and advection by currents and storm/wave activity), anthropogenic processes (such as transplantation of material during dredging; Brand, 1999; Butler et al., 2010), the inclusion of much older material through erosion of coastal strata (Wehmiller et al., 1995) and stratigraphic condensation at a variety of scales (Kidwell and Bosence, 1991; Gómez and Fernández-López, 1994). During the mixing processes that produce time-averaging, biotic remains also undergo taphonomic alteration and destruction. The process of taphonomic destruction in shell accumulations has been compared to the loss of radioisotopes during radioactive decay (Olszewski, 2004). This analogy suggests that the form and extent of *post mortem* taphonomic alteration of shell material might function as a proxy for time since death, and that the rate of taphonomic alteration and subsequent shell loss might in some circumstances operate in a way that can be approximated mathematically. Empirical studies are equivocal about this, some showing that taphonomic destruction of the remains of shelled marine organisms can be completed on time scales of the order of days to years (Cummins et al., 1986; Staff et al., 1986; Davies et al., 1989; Powell et al., 1989), while other research based on radiometric

* Corresponding author.
E-mail address: p.butler@exeter.ac.uk (P.G. Butler).

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and amino-acid age dating has demonstrated that shells in settings where taphonomic processes are active can survive relatively intact for 10s, 100s or even 1,000s of years (Flessa et al., 1993; Flessa and Kowalewski, 1994; Meldahl et al., 1997; Kowalewski et al., 1998; Carroll et al., 2003; Krause et al., 2010; Gabriel Dominguez et al., 2016). It seems likely that the relationship between shell survival, taphonomic condition and shell antiquity is very specific to the environmental setting of the accumulation.

Few studies have been carried out comparing shell condition with radiocarbon age, probably because of the significant cost of the large number of radiocarbon analyses that would be required. A number of empirical studies have employed amino-acid based techniques, although these studies have so far been geographically limited to the nearshore shelf areas of the tropical Southwestern United States (Powell et al., 1989; Powell and Davies, 1990; Meldahl et al., 1997; Kowalewski et al., 1998), or Brazil (Carroll et al., 2003). One other study used amino acid racemization to compare taphonomic characteristics of bivalves from the mid-Atlantic United States (Wehmiller et al., 1995). This study found that some taphonomic characteristics can be related to apparent age, albeit at very low time resolution because of the extended age range of the samples (modern – 39,500 ^{14}C yr BP). The data presented here are the first of which we are aware to investigate the relationship between radiometrically dated material and taphonomic character in the temperate North Atlantic region.

The shells used in this study come from the pan-Atlantic (Dahlgren et al., 2000) bivalve mollusc *Arctica islandica*, a genuinely remarkable animal which has been shown - using the distinct annual banding that can be observed in the shell - to be the longest-lived animal known to science whose precise longevity can be determined (507 years; Butler et al., 2013). The banding patterns in *A. islandica* are similar within populations, and a number of studies have now been published in which the patterns in shells of live-collected and subfossil specimens of *A. islandica* have been cross-dated and used to build absolutely dated chronologies of shell material (Witbaard et al., 1997; Butler et al., 2010, 2013; Holland et al., 2014; Mette et al., 2016; Bonitz et al., 2018). These chronologies can be used to reconstruct past marine environments at high resolution using the chronology indices (*i.e.* the detrended and averaged increment widths) or geochemical proxies in the shell carbonate (Schöne et al., 2005; Butler et al., 2009a, 2011; Mette et al., 2016; Reynolds et al., 2016; Estrella-Martínez et al., 2019a). As is made clear in some of the studies, the extension of chronologies back in time before the lifetime of the longest-lived live-collected specimen depends on the availability of sufficient quantities of dead shell material from the same population. Time-averaged deposits of shells from areas of minimal current transport are desirable for sclerochronological analyses as they act as a repository of climatic information over a long period of time at a single site (Flessa et al., 1993). In this sense, the shells of *A. islandica* have been found to be very suitable for chronology building, as radiocarbon dating of shells from single sites has shown a very wide range of dates of death (*e.g.* up to 8200 ^{14}C yr BP for shells from the Irish Sea (Butler et al., 2009a) and – reported in this paper - up to 12,500 ^{14}C yr BP for shells from the Fladen Ground, northern North Sea). The preferred habitat of *A. islandica*, just below the sediment-water interface in sandy and muddy sediments, enhances the likelihood of long-term burial (and hence protection against bioerosion), while the introduction of intensive commercial dredging in shelf sea waters over the past decades has likely mobilized many of these long buried shells, making them available for chronology development in relatively good condition (Brand, 1999; Butler et al., 2010). Such shell deposits occur widely in UK waters, for instance on the seabed of the Fladen Ground in the northern North Sea and off the west coast of the Isle of Man in the Irish Sea.

Building chronologies using shells from such time-averaged and condensed assemblages can be time consuming and potentially misleading because the wide range of ages in the assemblage enhances the likelihood that similar banding patterns will be found in shells that are in fact widely separated in time. Radiocarbon analyses can be used to obtain a first order approximation of time since death, but these are relatively expensive. The problem might potentially be mitigated if the taphonomic condition of *A. islandica* could be used as a reliable proxy for time since death. At the very least, an assessment of taphonomic condition could be used as "triage" for selecting individuals for radiocarbon dating. The availability of a large number (277 analyses) of radiocarbon analyses of *Arctica islandica* shells from periods in the Early Holocene/Lateglacial and throughout the past millennium has presented a unique opportunity to quantify the relationship between the taphonomic condition of a shell and time since death. The goal of this study is to quantify specific taphonomic characteristics of the shells (amount of remaining periostracum, presence and condition of the ligament, extent of erosion at the shell margin, amount of bioerosion, and nacre condition) and apply discriminant analysis and principal component analysis to determine whether particular combinations of these characteristics reliably indicate the time that has elapsed since the death of the animal that produced the shell.

2. Materials and methods

2.1. Sampling strategy

The Fladen Ground is located in the northern North Sea and forms part of the deeper shelf area between Scotland and Norway (Fig. 1). Water depths in the area sampled in this study range between 100 and 155 m. Soft muds typically cover wide flat areas of the Fladen Ground. The majority of the muddy sand and sandy mud seabed units, where *A. islandica* populations are located, are reworked from glacial, glaciomarine and glaciofluvial sediments following deglaciation in the North Sea Basin(Balson et al., 2002). These sediments form a predominantly flat seabed with little evidence of significant seabed sediment transport, and therefore, it can be assumed, minimal transport of *A. islandica* valves. Below the soft muds, and exposed in some areas, is the Holocene Witch Ground Formation (Weichselian Lateglacial to early Holocene; Johnson et al., 1993) which is known to contain some *A. islandica* valves. The *post mortem* exposure and transport of *A. islandica* valves is assumed to be minimal as a result of the burrowing habit of *A. islandica* and the occurrence of a large number of articulated valve pairs with minimal shell breakage would tend to support this supposition. The grain size of the present-day soft mud sediments and that of the Holocene Witch Ground Formation are virtually indistinguishable (Balson et al., 2002). Because the samples used in this study were dredged and not box cored, it is uncertain whether the valves recovered are recent *A. islandica* that burrowed into the Witch Ground Formation during their lifetimes, or long-dead individuals. Equally difficult to ascertain is whether the Early Holocene and Lateglacial *A. islandica* have been transported and condensed into shell lag deposits.

Several thousand shell valves and hundreds of live individuals of *Arctica islandica* were dredged from the seabed at depths between 100 and 155 m from nine stations in the Fladen Ground during two cruises in June 2001 and 2004 (Fig. 1; station A - 58° 49.86′N 0° 21.35′ W; station B - 59° 7.27′N 0° 10.00′ E; station C - 58° 47.24′N 0° 20.48′ E; station D - 58° 32.06′N 0° 10.04′ E; station F - 59° 23.00′N 0° 30.00′ E; station G - 58° 31.00′N 0° 25.00′ E; station H - 58° 22.52′N 0° 34.20′ E; station I - 58° 22.50′N 0° 31.00′ E; station J - 58° 5.13′N 0° 15.02′ E). Two hundred and seventy-seven of the dead valves were selected for AMS ^{14}C dating. Larger specimens (> 80 mm in shell height) were selected as it was assumed that these would also be relatively long-lived and therefore most useful for later sclerochronological analyses (see Scourse et al., 2006).

2.2. Quantification of taphonomic condition of the shell valves

The taphonomic condition of the shells was quantified using categorical measures of taphonomic alteration that have previously been

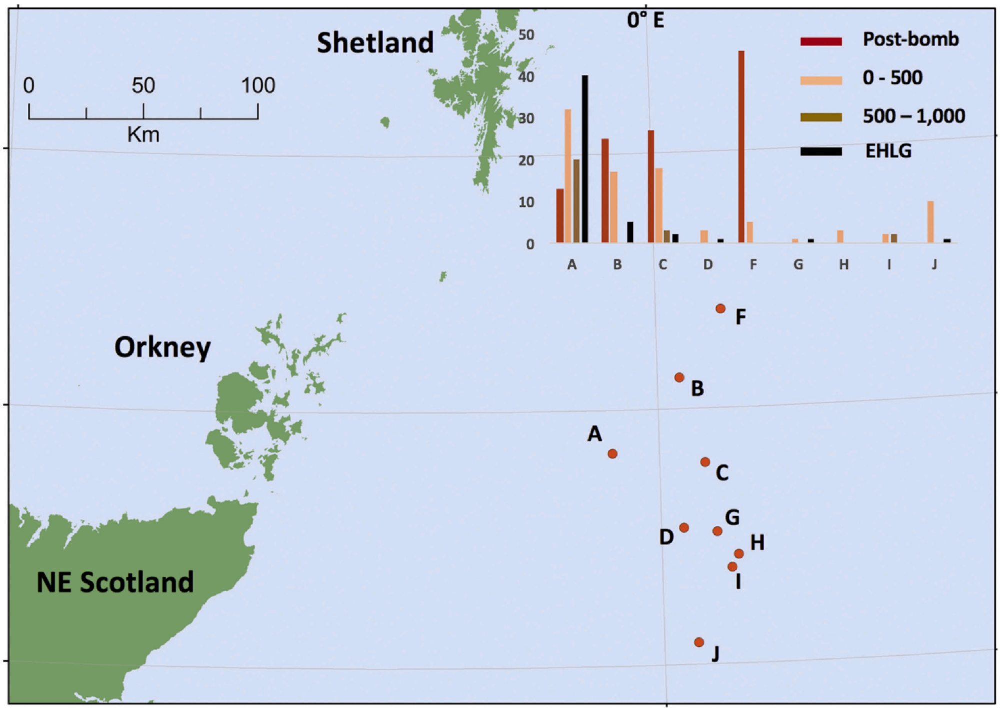

Fig. 1. The Fladen Ground, northern North Sea with the *Arctica islandica* collection stations indicated. The inset chart shows the numbers of shells of each age group collected at each station (see also Table 2); the Marine13 calibrated calendar ages for each age groups are: post-bomb (red; later than 0 yr BP); ~0–500 yr BP (pink); ~500–1000 yr BP (brown); EHLG (black) ~6000–14,000 yr BP. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
The criteria used for the taphonomic grading of shells of *Arctica islandica* (modified from Flessa et al., 1993).

More damaged/decayed			Condition index	More intact	
	1	2	3	4	5
Periostracum	5% or less	50% or less	50–90% remaining	More than 90% (only removed at umbo)	Intact
Ligament preservation	No ligament	Outer ligament only	Inner ligament present but deteriorating	Intact outer and inner ligaments	
Shell margin preservation	Major abrasion (large chunks missing)	Minor abrasion and/or chipping	Sharp, continuous margin	Periostracum extending beyond the shell margin	
Bioerosion	Extensive boring	Moderateboring	Minimal boring	No borings	
Condition of nacre within the pallial line	Flaky/bubbly	Etched/pitted	Smooth		

used (Flessa et al., 1993) to characterize the preservational state of individual fossils and/or fossil assemblages (Table 1). The taphonomic condition of the 277 *A. islandica* shells used for radiocarbon dating was determined using five criteria – condition of periostracum, condition of ligament, erosion and damage at the margin, bioerosion of the shell, and nacre condition.

2.3. Radiocarbon analysis

Samples of shell aragonite for radiocarbon analysis were removed from the outer margin of 277 *A. islandica* shell valves after first removing any remaining periostracum from the outer shell surface with a fine-grit (1400) grinding pad. The outer 20% by weight of each sample was removed by controlled hydrolysis with dilute hydrochloric acid. The sample was then rinsed in distilled water, dried and homogenised. A known weight of the pre-treated sample was hydrolysed to carbon dioxide (CO_2) using 85% orthophosphoric acid at 25 °C. The CO_2 was converted to graphite by Fe/Zn reduction (Slota et al., 1987). Shell samples from 246 specimens were individually prepared at the NERC Radiocarbon Laboratory and analysed on the 5MV NEC AMS at SUERC, East Kilbride, Scotland (Xu et al., 2004). The remaining 31 radiocarbon analyses were undertaken at the AMS Radiocarbon Facility, University of Aarhus, Denmark. The raw ^{14}C ages were corrected for the marine reservoir effect by subtracting 424 years (this being the recommended correction for the North Sea open ocean region: see Harkness, 1983)), and calibrated using the Marine13 calibration curve (Reimer et al., 2013) with version 4.3 of OxCal (Bronk Ramsey, 1995; Bronk Ramsey, 2009). Calibrated ages are reported here as cal yr BP at 1 standard error, where 0 cal yr BP corresponds to 1950 CE (Reimer et al., 2013). See Table S1 for the full list of radiocarbon samples with laboratory IDs.

2.4. Discriminant analysis and principal component analysis

To test the feasibility of the use of the taphonomic characteristics for predicting the approximate radiocarbon age, discriminant analysis and principal component analyses with the five taphonomic variables were undertaken for the 277 shells using the statistical package Past4 (Hammer et al., 2001). The taphonomic variable scores were normalized prior to the analyses to the range 1–5 so that the analyses would not be biased by the differing scales for each variable (see Table 1 and supplementary Table S2). The computational details of the discriminant analysis are described on page 116 of the Past4 reference manual (Hammer, 2020). For the discriminant analysis the shells were divided according to their Marine13-calibrated calendar ages into four "known" groups, defined as Early Holocene and Lateglacial (~6000–14,000 cal yr BP, abbreviated EHLG for brevity), 500–1000 cal yr BP, 0–500 cal yr BP, and post-bomb (shells with bomb-enhanced ^{14}C and shells whose Marine13-calibrated age places their date of death later than 1950 CE). The last three timescales are of immediate interest for the purposes of this project as they cover the target time period for the construction of an absolutely-dated 1000-year growth series chronology. See supplementary Table S1 for the details of the grouping.

The principal component analysis identified the amount of variance in the data accounted for by different combinations of the various taphonomic characteristics. The resulting principal components were then correlated with individual variables to calculate loadings.

3. Results

3.1. Distribution of radiocarbon dated material

The overall age distribution of radiocarbon dated *Arctica islandica* shells from the Fladen Ground (Table 2; Fig. 1) was found to be strongly bimodal with 227 specimens recorded from the last millennium (25 from the early part of the millennium, 91 from the second half of the millennium and 111 post-bomb) and 50 specimens from the EHLG group. Apart from one slightly more recent sample (~6160 cal yr BP) all the other shells in the EHLG group were ~ 8180 cal yr BP or earlier (Fig. 2).

The majority (253 out of 277; 91%) of the shells were collected at the four most northerly sites (site A (n = 105); B(47); C(50); and F(51); Fig. 1 and Table 2). Clear geographic biases are apparent in the distribution of the shells by radiocarbon age (Fig. 1, Table 2). Recently dead (post-bomb pulse) material dominated sampling in the northern part of the Fladen Ground (station F). This area is also the source of most of the living material (not reported here). Shells from the second half of the last millennium are fairly evenly distributed across the central part of the Fladen Ground, while those from the earlier part of the last millennium are concentrated at the westernmost Fladen Ground site (station A), which also sourced 80% of those from the EHLG. No living shells at all were found at site A.

In general, the proportions of post-bomb shells increased to the east and north, while that of EHLG shells increased to the west. Far fewer shells (24 out of 277; 9%) were collected at the southern sites D, G, H, I and J, and of these a large majority (19 out of 24: 79%) were from the period 0–500 cal yr BP. Most (183 out of 202; 91%) of the more recent material (from the past 500 years including post-bomb material) was collected at the northern stations (A, B, C and F). The easternmost of these stations (B, C, and F) also produced the largest numbers of live-collected specimens.

Table 2
Age groupings of radiocarbon dated shells collected from each station (see Fig. 1).

	Post-bomb	~0–500 cal yr BP	~500–1000 cal yr BP	EHLG	Total
A	13	32	20	40	105
B	25	17		5	47
C	27	18	3	2	50
D		3		1	4
F	46	5			51
G		1		1	2
H		3			3
I		2	2		4
J		10		1	11
Total	111	91	25	50	277

3.2. Predictive ability of taphonomic characteristics

Discriminant analysis using the five taphonomic characteristics had a certain amount of success placing the more modern (post-bomb pulse) shells (81.1% of these were correctly placed), but found it challenging to discriminate between the ages of any shells older than that, even groups (EHLG and 500–1000 yr BP) that were widely separated in time (Table 3 and Fig. 3). A relatively high proportion (68%) of shells from the 500–1000 yr BP group were correctly assigned, but the analysis showed a distinct bias in favour of this group, assigning it more than three times as many shells (84) as it actually contained (25). Consequently, the proportions of correctly assigned shells in the 0–500 yr BP and EHLG groups were reduced (39.6% and 20.0% respectively), and only 20.2% of the shells assigned to the 500–1000 yr BP group were correct. Roughly four-fifths (81.1%) of the post-bomb group were correctly assigned, with the remaining shells being assigned equally to the 0–500 cal yr BP and 500–1000 cal yr BP groups.

Given these results, it is unsurprising that principal component analysis does not indicate any clear groupings of the four age classes (Fig. 4). The first principal component accounts for 60% of variability (Table 4), but this is not associated particularly strongly with any of the taphonomic characteristics (Table 5). The highest loading for PC1 (0.59) is associated with shell margin condition, but this is not significantly higher than the other four categories, which range from 0.37 to 0.49 (Table 5). Nacre condition has a high loading in PC2 (0.87), but this is not significant since PC2 only accounts for 14% of the variance.

The taphonomic characteristics of all the shells used in this study are shown in supplementary Table S2.

4. Discussion

4.1. Shell distribution

Recent research has centred on the construction of growth increment width chronologies from live-collected *Arctica islandica* shells from various locations in the North Sea and elsewhere (*e.g.* Witbaard et al., 1997; Schöne et al., 2005; Butler et al., 2009b). This approach has been extended to include the construction of floating chronologies using radiocarbon dated shells from the last millennium (Scourse et al., 2006) and the Early Holocene (Estrella-Martínez et al., 2019b). The distribution of radiocarbon dated *A. islandica* shells obtained in the current study will in principle enable the growth increment series of appropriately dated shells to be analysed and crossdated in order to construct an increment width chronology for the last millennium. While no live *A. islandica* shells were collected from the westernmost station A, the shells in this part of the seabed appear to be highly time-averaged, containing *A. islandica* valves from across the last millennium, as well as a large proportion from the EHLG group. Station B is slightly less time-averaged, consisting mainly of live-collected shells and shells from across the last millennium, with a much lower proportion from the EHLG group. The aim of our research is to crossdate live-collected and recently dead *A. islandica* shells from adjacent stations (Butler et al., 2009b) and then link the absolutely-dated chronologies obtained from these shells to floating chronologies based on radiocarbon dated shells from other periods during the last millennium.

A significant recent development has been the publication of a floating chronology based on early Holocene shells (Estrella-Martínez et al., 2019b) with radiocarbon analyses indicating dates close to the 8.2 ka cold event in the North Atlantic (Keigwin et al., 2005). However, it will not be possible at this stage to link it to an absolutely-dated chronology for the northern North Sea because of an extended hiatus between ~7700 ^{14}C years BP and 1400 ^{14}C years BP (see Fig. 2). This hiatus probably indicates variability in the population distribution and/or density of *A. islandica* in the Fladen Ground.

The extent of shell abrasion and physical breakage at the shell margin, features that are usually associated with current transported

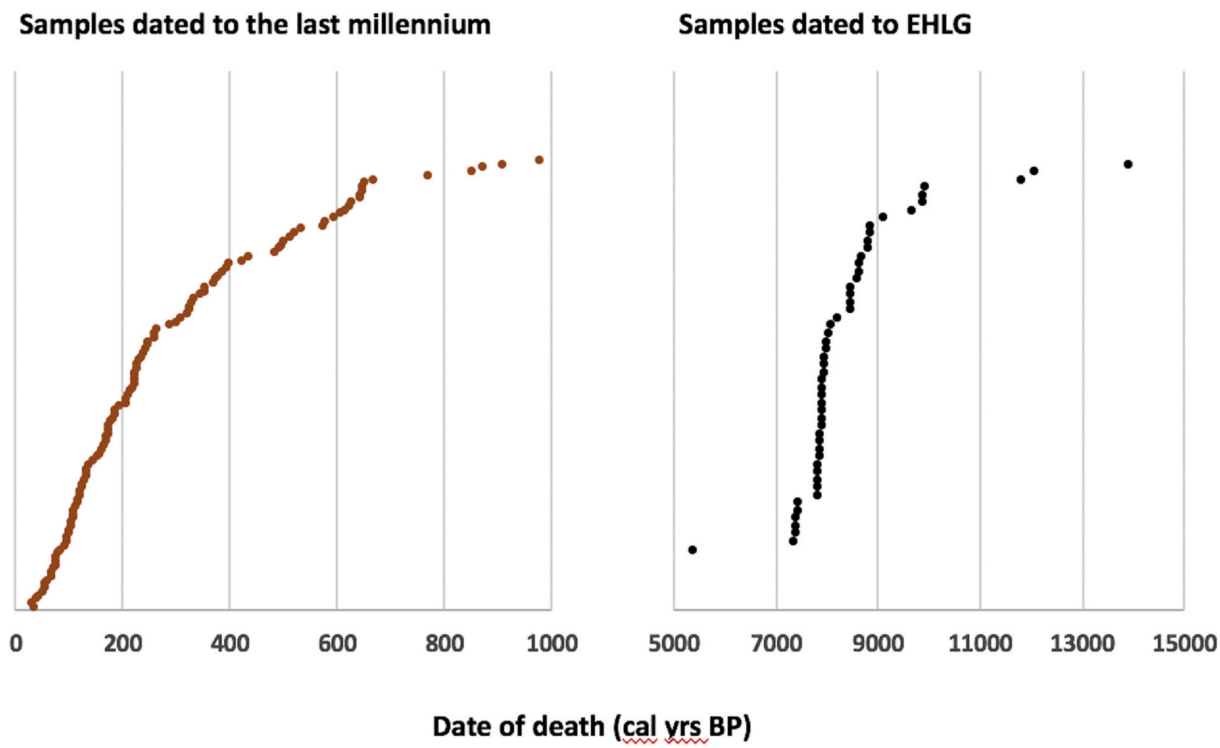

Fig. 2. Temporal distribution of 168 radiocarbon dated *Arctica islandica* shells from the Fladen Ground, calibrated using the Marine13 calibration curve (Reimer et al., 2013) and a marine reservoir correction of 424 years (see Harkness, 1983). The 109 shells with a calibrated date of death later than 1950 CE are not included. Because of the hiatus in the mid-Holocene the chart is separated into samples with a date of death within the last millennium (left) and those with a date of death in the Early Holocene/Lateglacial (right).

Table 3
Summary of the results of the discriminant analysis.

Actual group	Post-bomb	0–500 cal yr BP	500–1000 cal yr BP	EHLG	Total placed in each group	% correctly placed
Placement						
Post-bomb	**90***	18	1	0	**109**	**82.6**
0–500 cal yr BP	10	**36***	2	6	**54**	**66.6**
500–1000 cal yr BP	10	23	**17***	34	**84**	**20.2**
EHLG	1	14	5	**10***	**30**	**33.3**
Total in each group	**111**	**91**	**25**	**50**		
% correctly placed	**81.1**	**39.6**	**68.0**	**20.0**		

Numbers of shells correctly placed are shown as bold* on the main diagonal (n = 277, total correct = 153, percentage of correctly placed specimens = 55.2%). The percentages on the bottom row show the percentage of shells from each age group that were correctly placed, while the percentages in the right column show the percentage of shells assigned to each group that were correctly placed (see also Fig. 3).

material (Parsons, 1989), did not appreciably differ between shells collected from the western Fladen Ground (station A) and those from other sites. For this reason, the higher concentration of older (radiocarbon dated) specimens at the westernmost station A is unlikely to be the result of physical processes and *post mortem* transport**;** it may instead result from low-energy winnowing of the mud leaving little physical breakage but exposing EHLG *A. islandica* at the sediment-water interface. The observed distribution of last millennium specimens is interpreted as the result of environmental changes in the North Sea. Populations of *A. islandica* that were once abundant at the southernmost stations progressively died out while the northernmost populations were maintained through steady recruitment, resulting in a progressive northward shift of the range of living *A. islandica* populations. The presence of EHLG shells in the dredges is most likely a result of the erosion of Early Holocene and Lateglacial strata containing *A. islandica* shells (the Witch Ground Formation), together with more recent commercial dredging by scallop fishers (Brand, 1999).

4.2. Is taphonomy a useful dating tool in the Fladen Ground?

Statistical analyses did not support the hypothesis that the five taphonomic characteristics were reliable indicators of time since death of *A. islandica* specimens. The method was most successful with the most recent (post-bomb) shells which were also the shells with the least amount of taphonomic degradation. 81.1% of post-bomb shells were correctly placed, and 82.6% of the shells placed in the post-bomb group were correct (Table 3). If the method is to be useful, it needs to produce (as in this case) high levels of correct placement by both these criteria. For the remaining groups, either too few shells were correctly placed (39.6% for the 0–500 yr group) or too few of the shells assigned to the group were correct (20.2% for the 500–1000 yr group) or the method failed by both criteria (20% and 33.3% for the EHLG group).

The observed taphonomic condition of shells is a function of time of exposure in the taphonomically active zone (TAZ; Davies et al., 1989) where degradation is controlled by a combination of physical, biological and chemical activity. The time interval in the TAZ has been modelled by Olszewski (2004) as a function of the rates of reworking

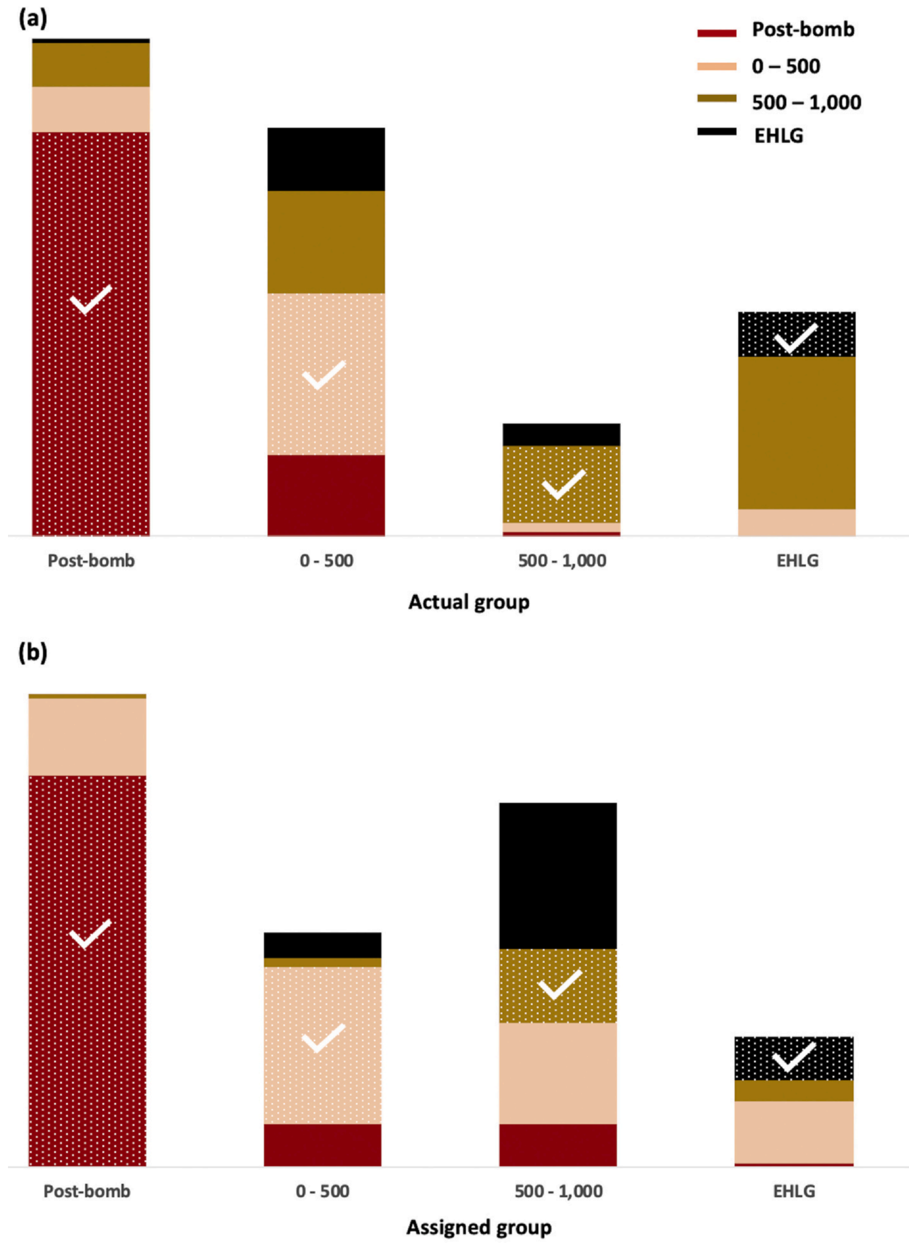

Fig. 3. Graphical summary of the results of discriminant analysis showing (a) placements of the shells from each age group and (b) assignments of the shells to each age group. The dotted areas with a tick mark indicate correct placements. For the taphonomy method of age assignment to be useful correct placements should make up a high proportion of both columns; this is the case for the post-bomb shells but not for any of the other groups.

and burial. This might lead to the conclusion that the EHLG *A. islandica* would be easily recognized by a complete lack of organic material (periostracum and ligament), abraded shell margins and discoloured or flaked nacre. However, some or all of these same characteristics are also found in most of the specimens from the two groups belonging to the last millennium, even though these have spent at least 6000 fewer years in the TAZ. The taphonomic method placed a full two-thirds (34) of the 50 EHLG shells in the 500–1000 cal yr BP group, indicating that very little further taphonomic change takes place between 1000 yr BP and 12,000 yr BP. One interesting observation, likely related to this physical stability, is that the discriminant analysis “centralized” the pre-bomb shells in the middle (500–1000 cal yr BP) of the three pre-bomb groups. Radiometric dating placed only 25 shells in this group, while the taphonomic discriminant analysis assigned it 84 shells (more than three times as many). By contrast the number of late millennium (0–500 cal yr BP) shells was reduced by the discriminant analysis from 91 to 54 and the number of EHLG shells was reduced from 50 to 30.

The results reported here indicate that significant taphonomic degradation of these large and robust shells is all but complete once the organic-rich parts of the shell (periostracum and ligament) have decayed, and as long as the shells remain buried and protected from bioerosion and physical damage their physical state changes little thereafter. Proportions of shells assigned to the EHLG (15.4% of 0–500 cal yr BP, 20% of 500–1000 cal yr BP and 20% of EHLG) suggest that this point of completion of significant physical change may be reached at any point after a few decades after death. There is some indication that more rapid change is taking place during the first 500 years after death (59% of 0–500 cal yr BP, but only 12% of 500–1000 cal yr BP and 12% of EHLG shells were assigned to the most recent (post-bomb and 0–500 cal yr BP) groups, but the rate of change is too inconsistent between shells to make it a reliable method of assigning dates. Therefore we conclude that taphonomic indicators in *A. islandica* in the North Sea are not useful for indicating the antiquity of shell valves on the centennial scale required for use in

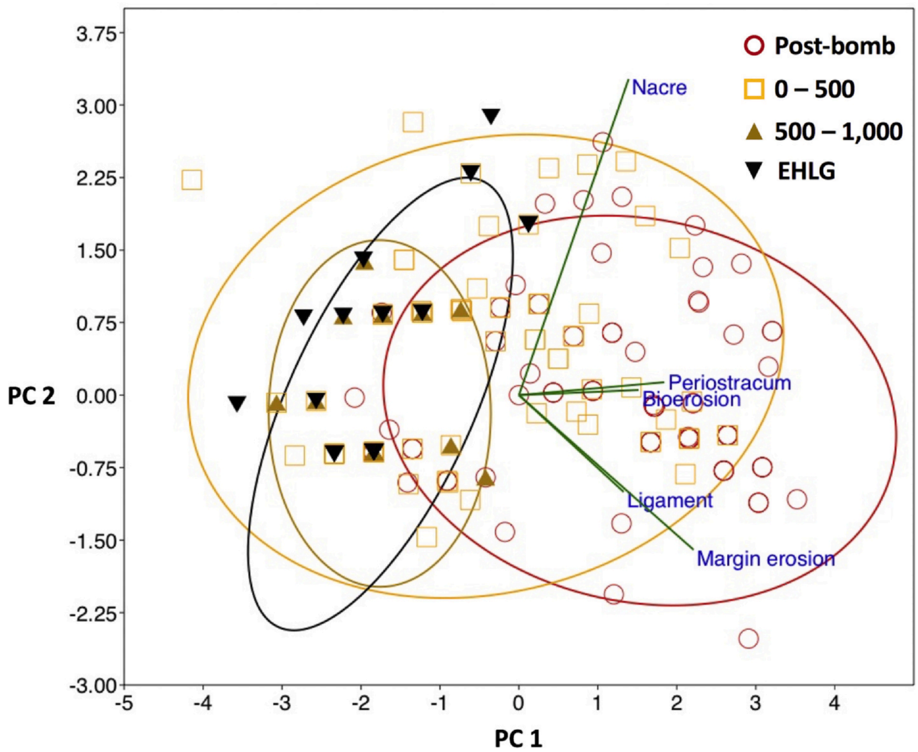

Fig. 4. Principal Component Analysis scores and loadings for PC1 and PC2.

Table 4
Results of the PCA Eigenanalysis showing the proportion of variance accounted for by each principal component.

	PC1	PC2	PC3	PC4	PC5
Eigenvalue	3.35	0.79	0.58	0.46	0.39
Proportion	0.60	0.14	0.10	0.08	0.69
Cumulative	0.60	0.75	0.85	0.93	1.00

Table 5
Correlation matrix of loadings of each principal component with each taphonomic character of the *Arctica islandica* shells.

Variable	PC1	PC2	PC3	PC4	PC5
Periostracum	0.49	0.04	−0.41	−0.24	−0.73
Ligament	0.35	−0.27	0.23	0.87	0.06
Shell Margin	0.59	−0.42	−0.66	−0.20	0.07
Bioerosion	0.40	0.01	0.52	−0.34	0.67
Nacre condition	0.37	0.87	−0.28	0.18	0.07

sclerochronological analysis.

5. Conclusions

Using a substantial set of radiocarbon analyses of shells of the bivalve mollusc *Arctica islandica* from the Fladen Ground in the northern North Sea, this study assessed the potential of shell condition index to provide a first order approximation of the antiquity of the shell. If successful, this method might provide a low-cost way to triage shells for use in chronology construction. However, while the shells of *A. islandica* are large and robust, their rate of taphonomic decay appears to be very dependent on their specific environment. Recently dead shells are successfully identified as recently dead, but for older shells the limit of detectable taphonomic change is reached, inconsistently, on timescales of decades to centuries, and it is therefore not possible to determine the antiquity of a shell with sufficient certainty for this method to be of any practical use in chronology construction.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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