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A new ΔR value for the southern North Sea and its application in coastal research

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Abstract

Accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dating of *Cerastoderma edule* (Linnaeus 1767) and *Mytilus edulis* (Linnaeus 1758) shells sampled in AD 1889 near the island of Wangerooge gave a new local correction factor ΔR of −85 ± 17 ^{14}C years for the Wadden Sea area. The value is considerably higher than the available scattered data from the North Sea, which were obtained from pre-bomb growth rings of living *Arctica islandica* (Linnaeus 1767). This can be explained by the incorporation of ^{14}C-depleted terrestrial carbon into the shell material which compensates the intensified exchange of CO_2 between atmosphere and shallow coastal water, e.g. by tidal currents. Additionally, two examples of application of the new Δ*R* value in coastal research give deeper insights into the dynamics of bivalve shell preservation in the Wadden Sea and the need for further research to clarify the Holocene reintroduction of *Mya arenaria* (Linnaeus 1758) into European waters.

Introduction

Radiocarbon dating of marine material such as bivalve shells or foraminifera tests requires an estimate of the marine reservoir effect, because the carbon reservoir of the oceans is depleted in ^{14}C compared to the atmosphere (Stuiver et al., 1986; Stuiver and Braziunas, 1993; Alves et al., 2018). This leads to discrepancies between radiocarbon ages for marine and terrestrial material of the same calendar age, the marine samples appearing on average 400 ^{14}C years older. For the mixed surface layer of the oceans, a global marine calibration curve exists (Marine20; Heaton et al., 2020). However, regional differences need to be corrected by including a specific offset ΔR (Stuiver et al., 1986; Reimer & Reimer, 2017). Rapid atmospheric ^{14}C changes are dampened in marine waters and the marine calibration curve appears 'smoothed' relative to the atmospheric one. Hence, the use of the marine calibration curve in combination with a local correction factor ΔR should be preferred over the use of the terrestrial calibration curve with a generalised estimated age correction for the marine reservoir effect (Reimer & Reimer, 2001).

The local offset ΔR can be determined by ^{14}C dating of pre-bomb (commonly pre-AD 1955) material either from long-lived species with an 'internal' age control by annual growth bands (e.g. corals or bivalves) or from specimens of museum collections with known collection date. To go deeper in time, the dating of reliable paired marine and terrestrial material obtained from the same chronostratigraphic context can be used (e.g. Facorellis et al., 2016).

For the North Sea area, available ΔR values show ambiguous results. In the Calib database (www.calib.org/marine), the closest ΔR values available for the German Wadden Sea area are data obtained from a living *Artica islandica* (Linnaeus 1767) individual collected in the German Bight (Weidman, 1995). Accelerator mass spectrometry (AMS) ^{14}C dating of annual pre-bomb growth rings (AD 1948, 1950 and 1954) of this long-lived bivalve resulted in ΔR values ranging from −189 ± 33 to 92 ± 116 years. This corresponds to reservoir ages between 219 and 488 ^{14}C years. In the Oyster Ground area (southern North Sea), Witbaard et al. (1994) measured ΔR values between −473 ± 74 and −120 ± 60 ^{14}C years for another *Arctica islandica* specimen. Finally, in fjords in northwestern Denmark, ΔR values obtained from several bivalve species vary from −32 ± 57 up to 375 ± 63 ^{14}C years (Heier-Nielsen et al., 1995). Therefore, a calendar age difference in the range of several hundred years must be expected for a marine ^{14}C date depending on the chosen reference for ΔR. This is particularly important when studying human-environment developments with possible leads and lags (Ascough et al., 2016).

Although coastal research, especially the reconstruction of former sea levels, largely relies on radiocarbon dating of inundated terrestrial material (e.g. basal peats; Meijles et al., 2018), dating of marine material is inevitable when reconstructing the dynamics of the sedimentation processes of the overlying marine sediments (e.g. Elschner et al., 2020). Here, terrestrial material is sparse or reworked, and often marine organisms that build calcium carbonate shells are the

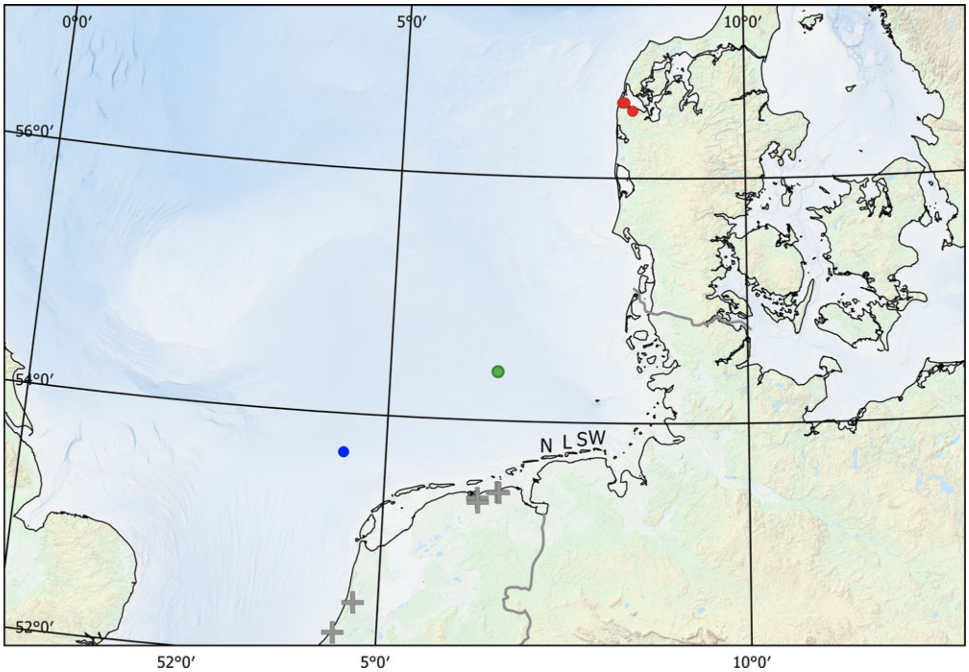

Fig. 1. Map of the southern North Sea area with the islands of Norderney (N), Langeoog (L), Spiekeroog (S) and Wangerooge (W). Additionally, locations are shown for which previous ΔR data are available: German Bight (green dot; Weidmann, 1995), Oyster Ground (blue dot; Witbaard et al., 1994) and Limfjorden (red dots; Heier-Nielsen et al., 1995). Crosses mark the positions of *Mya arenaria* shells of Essink et al. (2017). Data sources: DTM: EMODnet Bathymetry Consortium (2018) (http://doi.org/10.12770/18ff0d48-b203-4a65-94a9-5fd8b0ec35f6); coastline: EEA (www.eea.europa.eu/data-and-maps/data/); borders: Natural Earth (https://www.naturalearthdata.com).

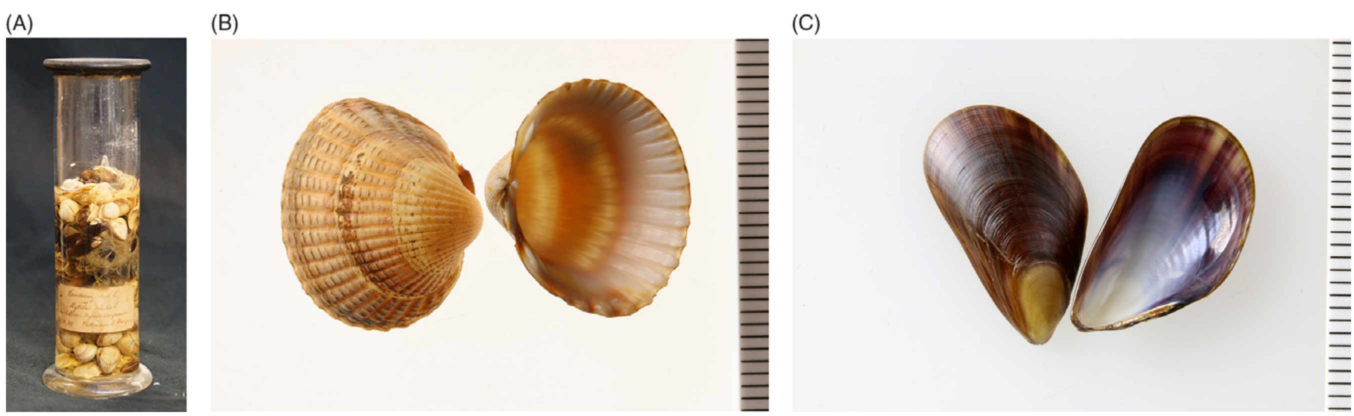

Fig. 2. Glas cylinder with the original, sealed bivalves sampled in AD 1889 around the island of Wangerooge (A) and close-up views of the dated specimens *Cerastoderma edule* (B) and *Mytilus edulis* (C). Scale in mm (photographs (B) and (C) by Rolf Kiepe, NIhK).

only available material for ^{14}C dating. Recently, transfer functions for relative sea-level changes based on assemblages of benthic foraminifera and ostracods have been established (e.g. Scheder et al., 2019). Sea-level reconstructions based on this approach also rely on ^{14}C dating of marine material for chronological control.

Within the WASA project (Bittmann et al., 2021) more than 60 samples of marine organisms have been ^{14}C dated in order to reconstruct coastal dynamics around the East Frisian island of Norderney. Thus, a local ΔR value for solid palaeoenvironmental reconstructions of this coastal environment is crucial. For example, suspension feeders such as *Cerastoderma edule* and *Mytilus edulis* may partially incorporate terrestrial carbon from nearby river discharge into the Wadden Sea. Poirier et al. (2019) hypothesise that coastal foraminifera take up ^{14}C-depleted carbon from terrestrial lignocellulose debris via an unexplored pathway involving bacteria. Thus, a considerable ΔR offset in carbonate shells of the Wadden Sea from the global marine calibration curve can be expected.

In this study, we present results of ^{14}C datings of shells from two bivalve specimens collected in the 19th century and demonstrate two exemplary applications of the obtained ΔR value.

Methods

At the Landesmuseum Natur und Mensch, Oldenburg, Germany, several juvenile specimens of *Cerastoderma edule* and *Mytilus edulis* (zoological taxonomy follows WoRMS, www.marinespecies.org) sampled in AD 1889 near the island of Wangerooge (Fig. 1) are stored in a sealed glass cylinder in a mixture of ethanol, glycerine and water (Fig. 2). In 2018, the original seal was broken and one specimen of each species was withdrawn. These were

Table 1. Reported ^{14}C ages of two bivalves collected in AD 1889 with resulting regional offset ΔR from the global marine calibration curve Marine20. Please note that an earlier reported value of ΔR based on the Marine13 calibration curve (Reimer et al., 2013) is 74 ± 16 ^{14}C years (Elschner et al., 2020).

Lab code	Species	^{14}C age (^{14}C years)	^{14}C error (1σ)	$\delta^{13}C$ (‰)	ΔR (^{14}C years)	ΔR error (1σ)
Poz-103589	*Mytilus edulis*	530	30	−0.5 ± 0.9	−95	30
Poz-103590	*Cerastoderma edule*[a]	544	21	−1.7 ± 0.5	−81	21
combined		540	17		−85	17

[a]This sample was dated with improved precision using two cathodes at the AMS laboratory in Poznań (573 ± 26 and 511 ± 27 ^{14}C years, respectively).

cooked in distilled water to remove the soft parts and the preserving agent. The shells were submitted to the Radiocarbon Laboratory, Poznań, Poland, where the ventral margin of one shell of each species was used for AMS ^{14}C dating. The pre-treatment of samples included the removal of organic coatings and the outer carbonate layers with H_2O_2 and HCl, respectively. CO_2 from the remaining material was obtained in a vacuum line by leaching with concentrated H_3PO_4 and was then reduced with H_2 to prepare an AMS target. The IAEA C1 Carrara Marble was used as background sample.

The shell of *Cerastoderma edule* was measured with improved precision, i.e. two cathodes were prepared, analysed and the data averaged by the Radiocarbon Laboratory in Poznań.

The resulting ^{14}C dates were used to calculate the local reservoir effect for the German Wadden Sea using the online application at http://calib.org/deltar/. Both ^{14}C dates were combined using equations given by Ward & Wilson (1978) by calculating a weighted mean, and the ΔR value of this combined age was determined in the same way.

Results and discussion

The obtained ^{14}C ages for *Mytilus edulis* (530 ± 30 ^{14}C years; Table 1) and *Cerastoderma edule* (544 ± 21 ^{14}C years) are statistically similar (X^2-test in Oxcal 4.3; Bronk Ramsey, 2009) and justify the calculation of a weighted mean. Similarly, Ascough et al. (2005) found no significant difference in the ^{14}C ages of several mollusc species from a distinct archaeological layer in Scotland. The resulting ΔR value of −85 ± 17 ^{14}C years (Table 1) represents the first estimate of the local marine reservoir effect for the German Wadden Sea area and corresponds to a reservoir age of 427 ^{14}C years.

This new ΔR value differs considerably from the previously available ΔR values of Weidman (1995) and Witbaard et al. (1994) for the German Bight and the Oyster Ground with weighted averages of −160 ± 93 ^{14}C years and −261 ± 155 ^{14}C years, respectively. These negative ΔR values imply the incorporation of carbon slightly enriched in ^{14}C (and hence reservoir ages <400 ^{14}C years), which can be explained by the hydrographical characteristics of the southern North Sea (Scourse et al., 2012). In these shallow waters and with relatively high primary production rates an enhanced exchange with the atmosphere takes place and the carbon reservoir of the sea water is comparably small. Located closer to the Strait of Dover, the Oyster Ground might be more affected by the inflow of Atlantic surface water into the North Sea. In contrast, the German Bight is affected by freshwater inflow from the Elbe, leading to lower salinity values (Janssen et al., 1999) and probably influencing the ^{14}C content by water depleted in ^{14}C (e.g. hardwater effect; Scourse et al., 2012). Philippsen (2013) reports reservoir ages of *c.*1900–3000 ^{14}C years from water dissolved inorganic carbon (DIC) of the Alster, a tributary of the Elbe. Reservoir effects of similar magnitude exist for the Waal, the main distributary branch of the Rhine (Lanting & Van der Plicht, 1998). A riverine influence may cause the less negative ΔR value obtained from the German Bight compared to the Oyster Ground.

In addition, the large variability within the data from the German Bight and the Oyster Ground is striking. In both studies, growth bands of *Arctica islandica* were analysed and showed variations of >100 ^{14}C years in ΔR within one or two decades. It is speculative if this variability can be attributed solely to actual changes in the reservoir age of the North Sea water, possibly due to changing current regimes, or if larger uncertainties in the early days of AMS-^{14}C dating also play a certain role (e.g. Chen et al., 2011).

Even though an intense mixing by tidal currents in the Wadden Sea should favour an atmosphere–sea CO_2 exchange, the new ΔR value obtained near the island of Wangerooge is considerably higher than at the two offshore sites. This might be because of a higher contribution of old, ^{14}C-depleted terrestrial/fluvial carbon to the marine DIC, for example by CO_2 originating from the decomposition of organic sediments such as peat (Lanting & Van der Plicht, 1998). Although all three bivalve species discussed here are suspension feeders, species effects may likewise play a role, e.g. differences in the contribution of metabolic carbon to the shell carbonate. Gillikin et al. (2006) report a variable percentage (between 0 and 10%) of metabolic carbon in shells of *Mytilus edulis*, whereas this percentage seems to be more constant and close to the theoretically derived 10% for *Arctica islandica* (Beirne et al., 2012).

For a specific location, ΔR values are generally assumed to be constant in time (Hua, 2013) due to the lack of data. However, models suggest a large temporal variability of several hundred years for the regional marine reservoir effect during the late Quaternary (Franke et al., 2008). Regarding the use of marine ^{14}C dates for the Wadden Sea, even variations of a few decades can be crucial (see applications below). Tisnérat-Laborde et al. (2010) have used ^{14}C analyses of mollusc shells collected between AD 1823 and 1952 mainly from the French Atlantic coast to infer changes in the marine reservoir effect. They report a mean ΔR value of −7 ± 50 ^{14}C years for the pre-anthropogenic period and considerable variations of the marine reservoir age from around 90 to 170 ^{14}C years for the period between AD 1885 and 1950. These differences are correlated to changes in ocean currents and therefore in reservoir sources.

Given the large but often non-catalogued collections in natural history museums in Germany and across Europe, there seems to be ample opportunity for future research on this topic.

Applications

1 Dating of marine bivalves from sediments of the East Frisian Islands

Within the WASA project (Bittmann et al., 2021), 38 of the more than 60 AMS ^{14}C-dated marine samples were bivalve shells (Table 2) with both valves still attached and partly occurring in

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Table 2. Compiled ^{14}C dates of bivalves for the Wadden Sea area of the East Frisian Islands. pMC: percentage of modern carbon.

	Lab code	Species	^{14}C age (^{14}C years)	Error (^{14}C years)	Project/reference
1	HV-22944	*Mya arenaria*	715	55	H. Freund, ICBM Wilhelmshaven
2	HV-22947	*Scrobicularia plana*	760	65	H. Freund, ICBM Wilhelmshaven
3	HV 22948	*Mya arenaria*	800	55	H. Freund, ICBM Wilhelmshaven
4	HV 22945	*Mya arenaria*	840	75	H. Freund, ICBM Wilhelmshaven
5	HV 24577	*Cerastoderma edule*	1030	45	H. Freund, ICBM Wilhelmshaven
6	HV 24576	*Cerastoderma edule*	1210	45	H. Freund, ICBM Wilhelmshaven
7	HV 22946	*Mya subtruncata*	1435	75	H. Freund, ICBM Wilhelmshaven
8	AA13211	*Cerastoderma edule*	631	59	Behrends et al., 2003
9	AA13213	*Cerastoderma edule*	2018	56	Behrends et al., 2003
10	AA13223	*Cerastoderma edule*	589	52	Behrends et al., 2003
11	AA13225	*Cerastoderma edule*	2112	55	Behrends et al., 2003
12	AA13226	*Cerastoderma edule*	737	52	Behrends et al., 2003
13	Poz-97987	*Barnea candida*	101.51 pM C	0.34	WASA project
14	Poz-95935	*Mya arenaria*	109.79 pM C	0.34	WASA project
15	Poz-93518	*Ensis siliqua*	113.45 pM C	0.35	WASA project
16	Poz-95930	*Cerastoderma edule*	117.74 pM C	0.35	WASA project
17	Poz-93519	*Cerastoderma edule*	123.08 pM C	0.37	WASA project
18	Poz-93517	*Cerastoderma edule*	123.57 pM C	0.37	WASA project
19	Poz-95929	*Ensis siliqua*	125.37 pM C	0.36	WASA project
20	Poz-93515	*Cerastoderma edule*	125.62 pM C	0.39	WASA project
21	Poz-93524	*Mya arenaria*	127.84 pM C	0.38	WASA project
22	Poz-93427	*Ensis siliqua*	128.24 pM C	0.40	WASA project
23	Poz-93428	*Ensis leei*	128.41 pM C	0.40	WASA project
24	Poz-93514	*Cerastoderma edule*	129.85 pM C	0.39	WASA project
25	Poz-93429	*Ensis leei*	130.02 pM C	0.39	WASA project
26	Poz-93521	*Ensis siliqua*	131.06 pM C	0.38	WASA project
27	Poz-95932	*Cerastoderma edule*	133.37 pM C	0.38	WASA project
28	Poz-100289	*Cerastoderma edule*	540	40	WASA project
29	Poz-93523	*Mytilus edulis*	560	30	WASA project
30	Poz-100382	*Mytilus edulis*	595	30	WASA project
31	Poz-97989	*Cerastoderma edule*	600	30	WASA project
32	Poz-95925	*Cerastoderma edule*	600	30	WASA project
33	Poz-93522	*Cerastoderma edule*	630	30	WASA project
34	Poz-97994	*Donax vittatus*	715	30	WASA project
35	Poz-95928	*Limecola balthica*	740	30	WASA project
36	Poz-93425	*Limecola balthica*	1330	30	WASA project
37	Poz-97990	*Barnea candida*	1350	30	WASA project
38	Poz-93422	*Cerastoderma edule*	1395	30	WASA project
39	Poz-95934	*Limecola balthica*	1400	30	WASA project
40	Poz-93424	*Cerastoderma edule*	1445	30	WASA project
41	Poz-100383	*Limecola balthica*	1510	30	WASA project
42	Poz-97986	*Spisula solida*	1510	30	WASA project
43	Poz-97993	*Mytilus edulis*	1535	30	WASA project

(*Continued*)

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Table 2. (*Continued*)

	Lab code	Species	^{14}C age (^{14}C years)	Error (^{14}C years)	Project/reference
44	Poz-100288	*Cerastoderma edule*	1540	30	WASA project
45	Poz-97991	*Limecola balthica*	1705	30	WASA project
46	Poz-93430	*Cerastoderma edule*	2260	30	WASA project
47	Poz-93426	*Cerastoderma edule*	2325	30	WASA project
48	Poz-95933	*Cerastoderma edule*	3000	30	WASA project
49	Poz-95926	*Cerastoderma edule*	4525	35	WASA project
50	Poz-97995	*Scrobicularia plana*	7360	30	WASA project

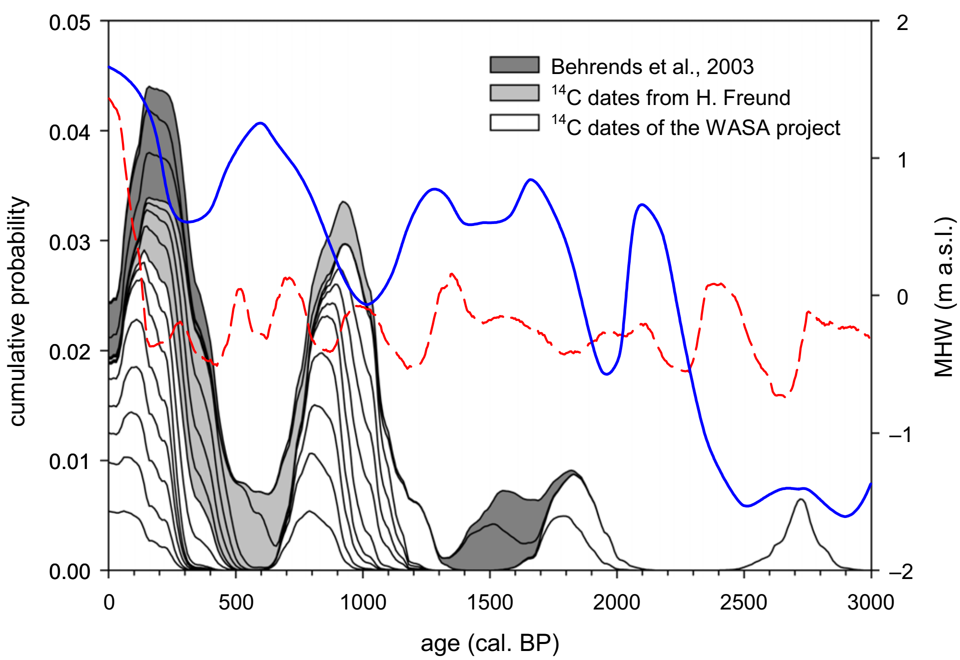

Fig. 3. Cumulative probability distribution for 35 marine ^{14}C dates of bivalve shells from the Wadden Sea around the East Frisian Islands. Blue line: sea-level curve (Behre, 2007); red line: 95% percentile based on a randomisation procedure as described in the text.

living position. They were sampled at various depths in sediment cores around the island of Norderney (Fig. 1). This dataset is complemented by seven previously unpublished ^{14}C dates from bivalves from Langeoog (H. Freund) as well as five ^{14}C measurements of *Cerastoderma edule* obtained around Spiekeroog published by Behrends et al. (2003; Table 2). Radiocarbon dates of *Cerastoderma edule* published by Flessa (1998) were not included, because this study focuses on reworked (transported) shells collected from surficial sediments. Articulated specimens were specifically excluded. No other published ^{14}C dates of marine bivalves are accessible from the Wadden Sea of the East Frisian Islands. Further available radiocarbon dates of pooled individuals of the foraminifera *Ammonia tepida* (Cushman 1926; WASA project) as well as dates obtained from the aquatic snail *Peringia ulvae* (Pennant 1777; courtesy of H. Freund) are not included in this example. In contrast to articulated bivalve shells, foraminifera and gastropods can potentially be reworked.

With the exception of two dates, all ^{14}C dates are younger than 3000 cal BP. Fifteen samples of the WASA project resulted in modern ages (percentage of modern carbon (pMC) > 100%) and will not be considered here. However, their young ages reflect the highly dynamic sedimentation processes in the Wadden Sea with localised, rapid sediment accumulation. For the remaining 35 samples, a cumulative probability distribution (cpd) was calculated in R (R Core Team, 2019) based on the algorithms provided in package CLAM (version 2.3.2; Blaauw, 2010) using the Marine20 calibration curve (Heaton et al., 2020) and our new ΔR value of −85 ± 17 ^{14}C years. Cumulative (or summed) radiocarbon probability distributions are commonly used in archaeology as a proxy record for human activity phases to be compared with palaeoenvironmental records (e.g. Feeser et al., 2019). However, Williams (2012) notes that false peaks can be obtained during the calibration process due to 'steep' portions in the calibration curve, whereas plateaus in the calibration curve will cause a dampening of peaks. To assess these effects, the following randomisation test was carried out: for the time period between 0 and 3000 cal BP, $n = 35$ calendar ages with an assumed error of 30 ^{14}C years were randomly selected from a uniform distribution, their radiocarbon age determined based on the Marine20 calibration curve and a ΔR of −85 ± 17 ^{14}C years and the cpd calculated as described above. This step was repeated 2000 times, and from the resulting dataset the 95% percentile was calculated. Any peak in the cpd of the original dataset that exceeds the 95% percentile of 2000 cpds of 35 randomly distributed ^{14}C dates can therefore be considered to be significant on a 95% level.

The results of these calculations are shown in Fig. 3, together with the sea-level curve obtained by Behre (2007). The cpd of the Wadden Sea ^{14}C dataset exhibits two prominent peaks at

Table 3. Reported ^{14}C dates of *Mya arenaria* by Essink et al. (2017). All highlighted calibrated age ranges include periods younger than AD 1492 and hence do not necessarily date the introduction of *Mya arenaria* to Europe before Columbus landed in America.

Lab code	^{14}C age (^{14}C years)	^{14}C error (^{14}C years)	Reservoir age (^{14}C years)	Reported 2σ calibrated age range (years AD)	Recalibrated 2σ age range with ΔR = −85 ± 17 (years AD)
GrN 26651	1000	20	400	1300–1405	1311–1541
GrN 18009	1015	20	400	1275–1425	1306–1525
GrN 32873	1000	50	400	1290–1415	1296–1578
GrN 32849	885	50	400	1310–1495; 1600–1615	1403–1681
GrN 31434	910	20	400	1405–1440	1406–1646
GrN 32940	900	45	400	1315–1465	1397–1669
GrN 738	955	50	400	1300–1440	1330–1628
GrA 61270	1110	40	840	1485–1800	not recalibrated[a]

[a]See text for discussion.

*c.*100–350 cal BP and 800–1000 cal BP exceeding the 95% percentile level. In contrast, only a few ^{14}C dates cover the time periods 500–650 cal BP and 1350–1600 cal BP. These intervals coincide remarkably with phases of rising sea levels (peaks in the cpd) as identified by Behre (2007) and phases with relatively stable sea level (few ^{14}C dates and low cpd). Apparently, bivalves are preserved in the sediment record during transgressive phases and presumably rapid sediment deposition. During phases of relatively stable sea level, highly dynamic processes of erosion and redeposition of sediments in the Wadden Sea probably prevented the sedimentological conservation of bivalves in living position. Articulated bivalves were preferentially preserved during phases of rapidly rising sea levels when a net accumulation of sediments prevailed and the abrasion base of the sea moved upwards. These findings are in agreement with conclusions of Brett (1995) who states that conservation *Lagerstätten* are typically found during transgressive and early highstand phases.

Although the dataset used is still limited (e.g. by its small sample size) and an (unintentional) sampling bias cannot be excluded, it suggests a remarkable relationship between taphonomic preservation and sediment dynamics controlled by sea-level changes.

2 ^{14}C dates and the timing of Mya arenaria *introduction to the eastern North Atlantic*

In a recent study, Essink et al. (2017) analysed a total of eight specimens of the marine bivalve *Mya arenaria* (Linnaeus 1758), which were found in sediment records at several sites in the Netherlands (Fig. 1). *Mya arenaria* disappeared in Europe during the Pleistocene (Strasser, 1999) until its reintroduction from North America, either by French colonisers or earlier by Vikings (Norse) via Greenland. Originally, the *Mya arenaria* shells were ^{14}C-dated and calibrated using the atmospheric calibration curve (Intcal13; Reimer et al., 2013) with an estimated reservoir age of 400 ^{14}C years for fully marine specimens and 840 ^{14}C years (Essink et al., 2017) for a sample with riverine influence. The ranges of these calibrated dates predate the landing on the American continent of Columbus in AD 1492, and therefore an introduction of this species to Europe by Viking settlers from northeastern North America was postulated. This hypothesis seems to be supported by additional datings of *Mya arenaria*. Petersen et al. (1992) reported an age of AD 1245–1295 for northern Denmark, and Behrends et al. (2005) dated *Mya arenaria* shells in the southern Baltic Sea to AD 1310 ± 70 years using aspartic acid racemisation.

When recalibrating the dates reported by Essink et al. (2017) with Calib 8.2 (Stuiver et al. 2020) using the Marine20 calibration curve and the new ΔR value of −85 ± 17 ^{14}C years, all seven recalibrated samples might be younger than AD 1492 (Table 3). The age of *Mya arenaria* published by Petersen et al. (1992) is lacking crucial information such as the original ^{14}C age and a possibly applied marine reservoir correction and can therefore not be recalibrated. The aspartic acid racemisation method applied on *Mya arenaria* samples from the Baltic Sea relies itself on cross-calibration against ^{14}C-dated bivalves from the Wadden Sea (Behrends et al., 2005). For this, several samples of *Cerastoderma edule* shells were ^{14}C-dated and calibrated using a reservoir age of 377 ± 16 ^{14}C years (Behrends et al., 2003). Although detailed information is lacking, it is likely that recalibration of these dates will change this cross-calibration and lead to a new assessment of these results, especially if slower racemisation rates are also taken into account (Behrends et al., 2005). In addition, a direct ^{14}C dating of these samples would be preferable for comparison, using available ΔR values for the Baltic Sea for calibration (e.g. Lougheed et al., 2013).

In contrast to the conclusion by Essink et al. (2017), the recalibrated ^{14}C age ranges do not provide conclusive evidence to support the hypothesis of an introduction of *Mya arenaria* to the European North Atlantic prior to Columbus' contact with the American continent. More ^{14}C dates of *Mya arenaria* and solid estimates of ΔR values for the Dutch Wadden Sea and of this particular timespan are necessary to solve this question.

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