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*The Holocene* 2006; 16; 967
DOI: 10.1177/0959683606hl987rp



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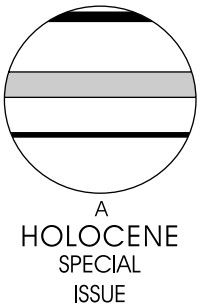
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*The Holocene* 16,7 (2006) pp. 967–974

# First cross-matched floating chronology from the marine fossil record: data from growth lines of the long-lived bivalve mollusc *Arctica islandica*

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**Abstract:** Integrated understanding of phasings within the climate system over the last glacial cycle, and at higher frequencies, is inhibited because no absolute timescale for the marine environment currently exists. This precludes identification of forcings and feedbacks, accurate temporal calibration of the marine radiocarbon reservoir effect, and the application of radiocarbon as a proxy of short-timescale ocean ventilation. This has prompted a search for annually banded marine proxies in the hope of establishing an accurate marine chronometer. We present annual growth band series from dead-collected specimens of the long-lived bivalve mollusc *Arctica islandica* from the northern North Sea and demonstrate their successful cross-matching, with the general timescale context independently verified by radiocarbon dating. Though at present limited to only a few statistically cross-matched series, this has already generated the longest *Arctica* chronology, and the first 'floating' chronology constructed entirely from marine fossils. The record covers the period from *c.* AD 1000 to 1400 and integrates a 267-yr series from the longest-lived *Arctica* specimen yet recorded from the North Sea. This breakthrough in cross-matching demonstrates that *Arctica islandica* can fulfill its potential as the 'tree of the sea' to provide an absolute timescale for the marine environment.

**Key words:** *Arctica islandica*, sclerochronology, cross-matching, Mediaeval, North Sea, HOLSMEER project.

## Introduction

Attempts to understand forcings and feedbacks within the global climate system, and to characterize natural climate variability, require phasings between the atmosphere, hydrosphere and cryosphere to be precisely defined (Hegerl, 1998). This necessitates the construction of accurate, reliable and exact age models. Phase-locking approaches (eg, Waelbroeck *et al.*, 2001), notably involving the use of the Greenland ice core records (Björck *et al.*, 1998; Johnsen *et al.*, 2001) for the last climate cycle (last 25 ka), have developed as a result of the problems associated with radiocarbon dating as a tool for constructing age models in high-resolution palaeoclimate studies. This approach assumes synchronicity in the climate system and cannot, by definition, identify phasing feedbacks between different components of the system.

Annually banded biotic records from both terrestrial archives, notably tree-rings (eg, Briffa *et al.*, 2004) and marine archives, including coral (eg, McCulloch *et al.*, 1999) and bivalve mollusc (eg, Witbaard *et al.*, 1997), are therefore critical; their integrated independent (and with replication, exact) age models can provide calibration for radiometric methods, notably radiocarbon, and, in conjunction with well-calibrated proxies of palaeoenvironmental change, enable such phasings to be identified. To date there is no continuous postglacial cross-matched annually banded chronology from the marine environment with which to

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10.1177/0959683606hl987rp

compare with terrestrial records. Only cross-matching 'ensures the absolute timescale' (Briffa, 1995: 80). Last climate cycle palaeoceanographic data derive largely from sediment records using radiocarbon-derived or wiggle-matched phase-locked age models (Waelbroeck *et al*., 2001). The former is a particular problem because the marine reservoir effect is known to vary in both space and time (Austin *et al*., 1995). No annually banded archive has been available for continuous calibration of the marine reservoir effect through time.

Time-series of environmental change using geochemical (stable isotope, trace element) proxies from annually banded marine sclerochronological (coral, mollusc) records have hitherto been constrained to the lifespan of live-collected individuals (Marchitto *et al*., 2000; Schöne *et al*., 2003, 2004) or to non-cross-matched chronologies of approximate age constrained by independent dating methods, notably radiocarbon or uranium-series dating (Tudhope *et al*., 2001). The construction of a long, absolute, timeseries beyond an individual lifespan demands statistically significant cross-matching of timeseries from different specimens or individuals. Our chronology is based on independently dated cross-matched valves of the long-lived bivalve mollusc *Arctica islandica* (Linnaeus 1767), the ocean quahog, collected by trawl from the Fladen Ground, northern North Sea (Figure 1).

Bivalve mollusc valves contain a record of their ontogeny in the form of internal annual growth lines, and higher resolution daily and tidal bands, which can be observed microscopically in acetate peel replicas (Figure 2) or thin sections (Richardson, 2001). The shell of *A. islandica* is deposited as a series of annual growth increments (fast growth) separated by narrow growth lines (slow growth or cessation of growth) (Jones, 1983; Witbaard, 1997). The annual nature of the increment has been demonstrated on the basis of seasonal stable oxygen isotope profiles (Weidman and Jones, 1994; Witbaard *et al*., 1994) and mark-recapture experiments (Ropes, 1988). Using this methodology, *A. islandica* has been identified as the longest-lived bivalve mollusc species known, frequently exceeding 150 years and with a longevity of up to 220 years (Jones, 1983). A recently published record from Iceland reports an individual with 374 growth increments (Schöne *et al*., 2005). Its potential as the 'tree of the sea' (Witbaard, 1997; Witbaard *et al*., 1997) and consequently as a sclerochronological tool in palaeoceanography (Jones, 1983; Weidman and Jones, 1994) has long been recognized. The potential correlation of the growth records between coeval individuals depends on the *a priori* assumption that different individuals within a population respond to the same environmental factors and thus display synchronous growth. Some short cross-matched chronologies based on live-collected material have been reported from the eastern Atlantic (Marchitto *et al*., 2000) and from the North Sea (Schöne *et al*., 2003), supporting this hypothesis. A recent model linking *A. islandica* growth to copepod abundance in the North Sea (Witbaard *et al*., 2003) has been used to interpret growth band increment variability from live-collected specimens from the southern and northern North Sea as a proxy for the winter North Atlantic Oscillation (wNAO) index (Schöne *et al*., 2003). Clearly the construction of rigorous annually resolved age models from this archive is an imperative, given the potential for this species to provide proxy palaeoceanographic or palaeoenvironmental data (Weidman and Jones, 1994; Schöne *et al*., 2004). The publication of such proxy data from this archive, is, however, premature if the series is not exactly dated, since correlations with other data sets will be fallacious. The aim of the study was therefore to investigate whether the cross-matching procedures used routinely in dendrochronology can be applied to *A. islandica* valves in order to construct long absolute chronologies. If they can, then this paves the way for ultra-high-resolution proxy palaeoenvironmental reconstructions of the marine environment based on age models without error and also enables continuous calibration of the marine reservoir effect.

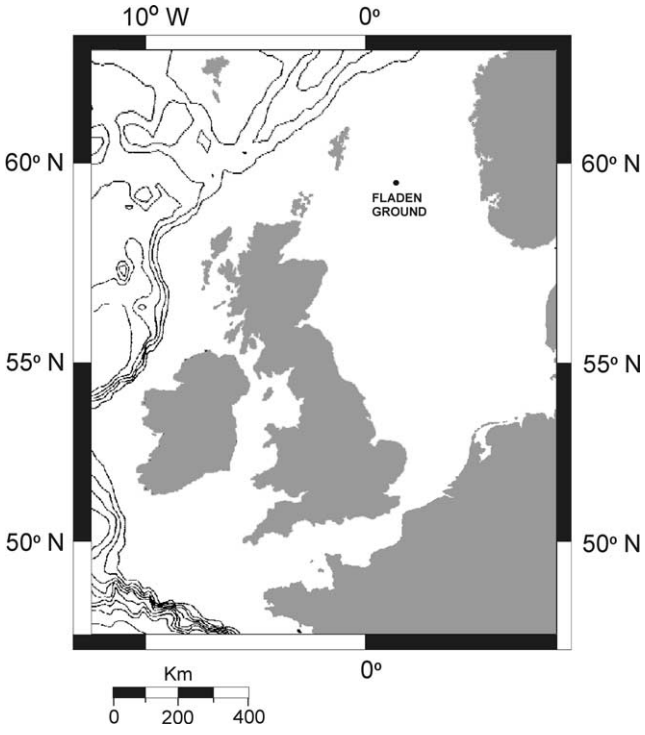



**Figure 1** Location of *A. islandica* specimens collected from the Fladen Ground, northern North Sea. The valves used to construct the chronology were dead-collected in a single trawl by the RV *Scotia* in 2001 (s01 trawl 197) in 115 m water depth at 58°49.86′N, 0°21.35′W

## Materials and methods

Live, dead articulated and dead single valves of *Arctica islandica* were collected in 2001 by trawling the seabed in the Fladen Ground, northern North Sea (Figure 1). All the dead-collected valves reported in this paper were collected in a single trawl from the RV *Scotia* (s01 trawl 197) in 115 m water depth at 58°49.86′N, 0°21.35′W. This trawl contained no live, five dead articulated and 87 dead single valves in the size fraction $>80$ mm length; specimens of length $<80$ mm have not been routinely logged as their longevity is usually too short for cross-matching, ie, less than 50 growth increments. The long-lived live-collected specimen reported was collected in trawl s01 189 at location 58°47.24′N, 0°20.48′E in a water depth of 125 m.

The annually resolved growth lines were identified in acetate peel replicas (Richardson, 2001) of polished and etched shell sections of the hinge plate in the umbo of the shell (Figure 2). Shells were embedded in resin and sectioned from the umbo to the shell rim using a diamond saw, ground on progressively finer grades of carborundum paper and polished with diamond paste and etched in 0.1M HCl for 2 min. Acetate peel replicas of the polished and etched surfaces were prepared and examined in transmitted light under magnifications of $\times 2.5$, $\times 4$ and $\times 10$. Following the production of acetate peel replicas, annual growth increment widths can be measured and recorded either from the shell valve (eg, Schöne *et al*., 2003) or along the hinge plate in the umbo. The hinge plate was

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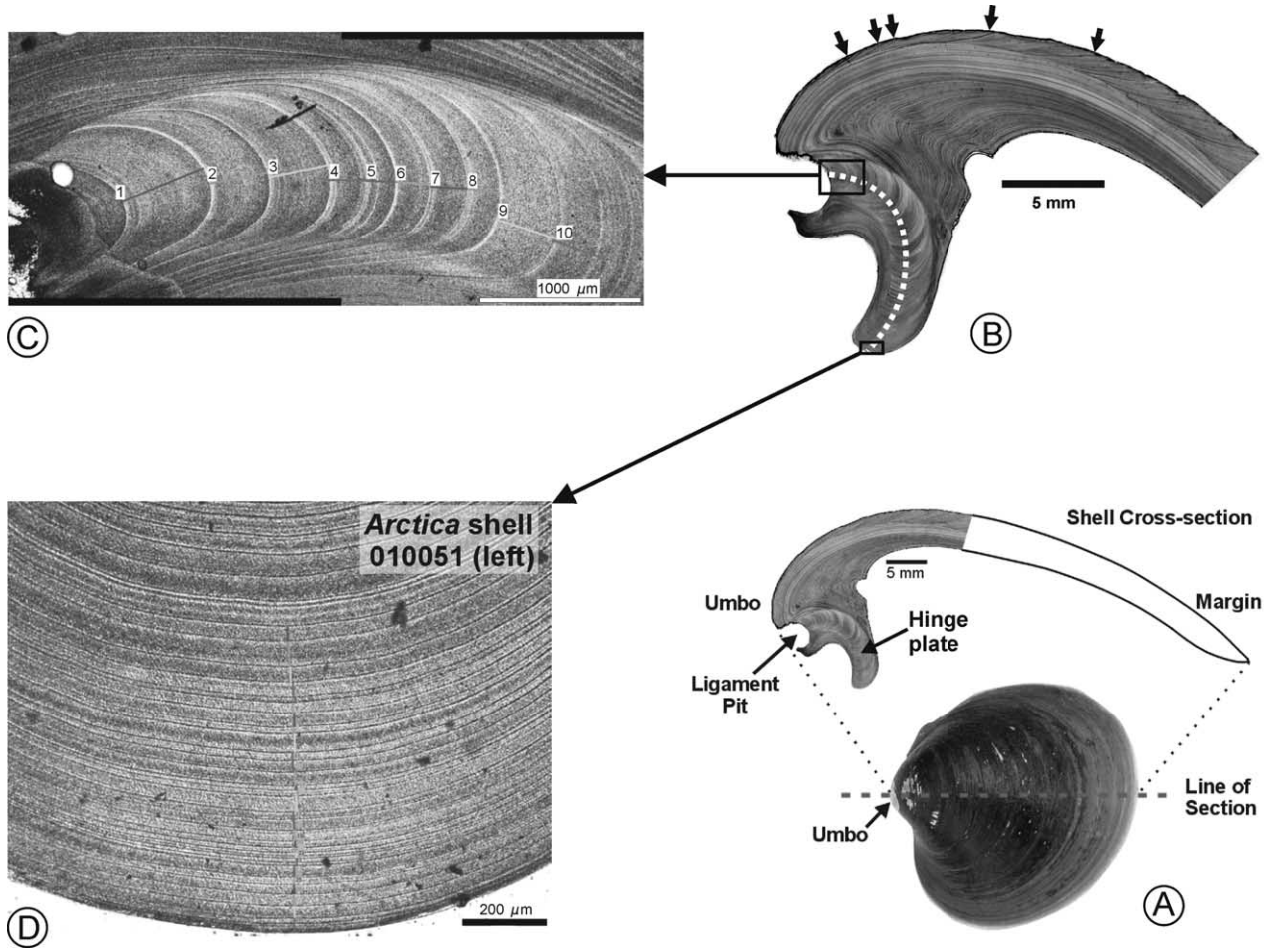



**Figure 2** (A) External valve face, showing line of section through *Arctica* valve used to generate acetate peel replicas. (B) Acetate peel replica cross-section of valve showing annual growth band increments along shell margin (arrows) and within the hinge plate. The axis of growth through the hinge plate used to generate increment data is indicated by the dashed white line. (C) Numbered annual growth bands are measured from the earliest growth bands to the most recent along the axis of growth. Juvenile early bands are wide and reflect the ontogenetic growth curve of the individual (Figure 3). (D) Narrow senescent late bands from the outer part of the hinge plate axis. Youngest increment at base

used since the growth increments here are clear (Figure 2), the axis of growth is reproducible from one shell to another and this part of the shell generally is not subject to external abrasion and erosion. Senescent growth increments can be as narrow as 5 μm; the mean measurement error on shell 010099 is $\pm$1.48 μm per growth increment (one standard deviation over 267 growth increments); furthermore this shell was measured by two independent operators. Images of the incremental record in the sectioned hinge plates were captured using a digital camera and the increment widths measured using the software analySIS® 3.2. This system facilitates increment measurement using an automated cursor that feeds directly into a data spreadsheet and enables both the growth increment series and their axis of measurement to be digitized. This enables the increment series, and their measurement, to be re-examined if the cross-matching identifies apparently missing or double increments. Because of the nature of the *Arctica* growth curve, where yearly growth can vary by two orders of magnitude over the life of the animal, the raw increment-width data are treated using a high-pass filter that removes the low-frequency ontogenetic growth curve (Figure 3) to produce a standard shell growth-increment plot for each shell (Figure 4). This involves generating the natural logarithm of the data to remove the different orders of magnitude and the residuals are then taken from a 15-yr spline through the data.

A newly developed program, SHELLCORR, which is an extension of the dendrochronological computer program COFECHA (Grissino-Mayer, 2001) was used to generate graphical output, to cross-match the growth-increment series between shells. COFECHA takes a correlation-based approach that has been used to compare the relative magnitudes of interannual tree ring-width variations (after some form of high-pass filtering) between different trees, or between a sample series and a 'master' reference chronology. Systematic comparisons are performed for all possible overlaps between the series. At each overlap, correlations are calculated for a series of overlapping time windows; 50-yr periods overlapping by a 21-yr window width were used in this study. High correlations produced at a constant offset between the different tree-ring series for all time windows is indicative of a correct temporal alignment between them at the indicated offset. Any sudden shift in the 'best-correlation' offset, if maintained in subsequent moving window comparisons, suggests that an error in the relative dating of one series against the other has occurred, possibly because a ring boundary has been missed in one series or a single ring in the other has been counted as two. By comparing data from many trees, COFECHA can confirm consistent relative alignment between series, and when the data are compared against an already-dated series, the program can be used to assign correct absolute dates to the rings in the entire series. SHELLCORR (written by IH in Matlab) follows the COFECHA concept of rigorous cross-matching of growth layer series by correlating segments of one series against another at different time lags.. However, instead of ranking

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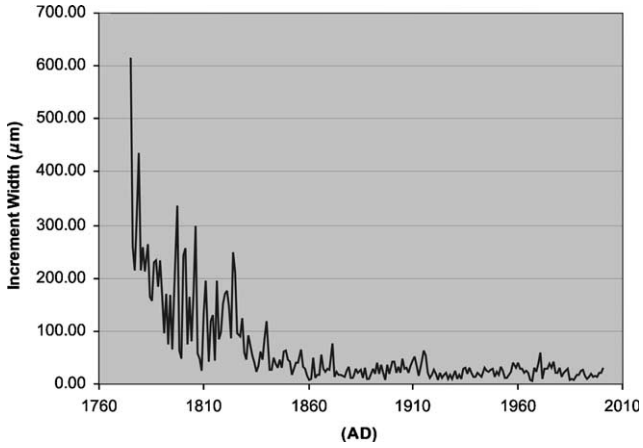



**Figure 3** Untreated growth band series from longest-lived live collected shell 010036 (211 years) collected from Fladen Ground in 2001 (RV *Scotia* trawl s01 189, 58°47.24′N, 0°20.48′E, 125 m water depth)

the best correlations within given constraints, it then presents all the results graphically in a colour-coded plot. This enables strong and consistent correlations to be seen in context (Figure 5). The format also shows clearly where growth increments might have been misidentified – for example, where two or more increments have been measured within a single year – or series in which specific year lines are missing. This analysis enables the lag of strong running correlations to be identified.

Samples for AMS $^{14}$C dating were taken from the umbo and/or margin of selected shells. Samples from the margin were removed using a hand-held dental drill, cleaned with 0.01M HCl between samples. Samples from the umbo were sampled opportunistically during the sawing process prior to resin embedding. For valves with both umbo and margin dates this effectively constrains the age, within the conventional errors, of the beginning and end of each valve series. Because the early juvenile growth increments are so much wider than the mature, senescent, increments, the umbo samples integrate only one or two years growth, but the margin samples integrate up to ten years growth.

## Results

We analysed growth line series from multiple live- and dead-collected shells trawled from the Fladen Ground (Figure 5). Whilst strong correlations between some live-collected shells were apparent at the expected 0-yr lag (Figure 5C/5D), no significant correlations were found between any live- and dead-collected shells in the material trawled in 2001. Our longest series generated from live-collected material is therefore currently limited to the longevity of the longest-lived live-collected specimen so far identified. This is shell 010036 which is 211 years old, providing a record from 2001 back to AD 1790 (umbo-rim length 81.9 mm). (Reference numbers relate to School of Ocean Sciences (UWB) *Arctica islandica* specimen collection.)

One heavily calcified large (umbo-rim length 105.5 mm) dead-collected right valve, specimen 010099, contains 267 annual bands (Figure 4). This specimen significantly cross-matches with two other dead-collected valves from the same trawl, left valves 010088 (Figure 5A/B) and 010090 (Figure 6). Specimen 010088 contains 117 annual bands and 010090 227 annual bands (Figure 6).

Shell carbonate (aragonite) samples from umbo (start of growth series) and margin (end of growth series) from these cross-matched valves were dated using AMS $^{14}$C in order to test whether these strong correlations were spurious. An additional loose flake from the umbo of shell 010099 (AAR-7733; Table 1) was also submitted for dating in order to test reproducibility (Figure 6; Table 1).

The $^{14}$C data demonstrate that all three valves (010099, 010088 and 010090) date from the Mediaeval period, broadly between AD 1000 and AD 1400, and that, at the 1σ level using the intercept method based on the marine calibration curve with $\Delta R = 0$ (400-yr reservoir correction; Harkness, 1983),

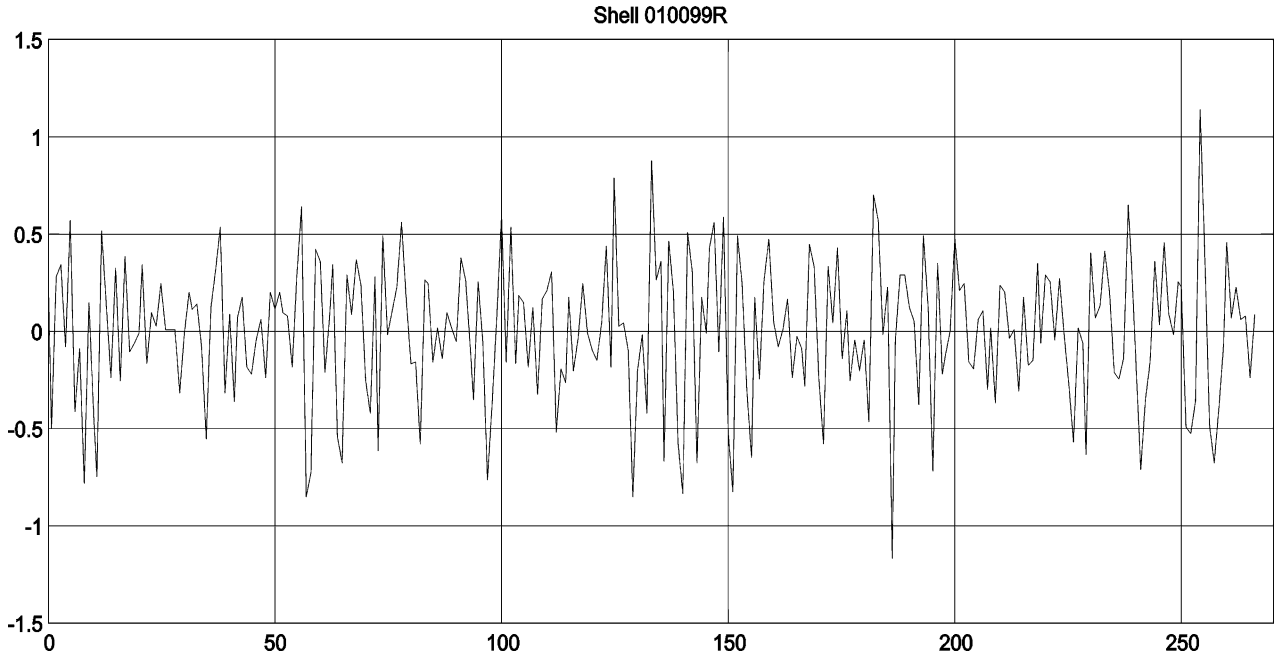



**Figure 4** Normalized shell growth plot for longest-lived shell 010099 (267 years) on arbitrary annual timescale; this shell was collected dead. A logarithmic function (unique to each individual) is first applied to the raw data series; the data are then normalized and the residuals from a 15-yr spline calculated producing a standard shell growth plot

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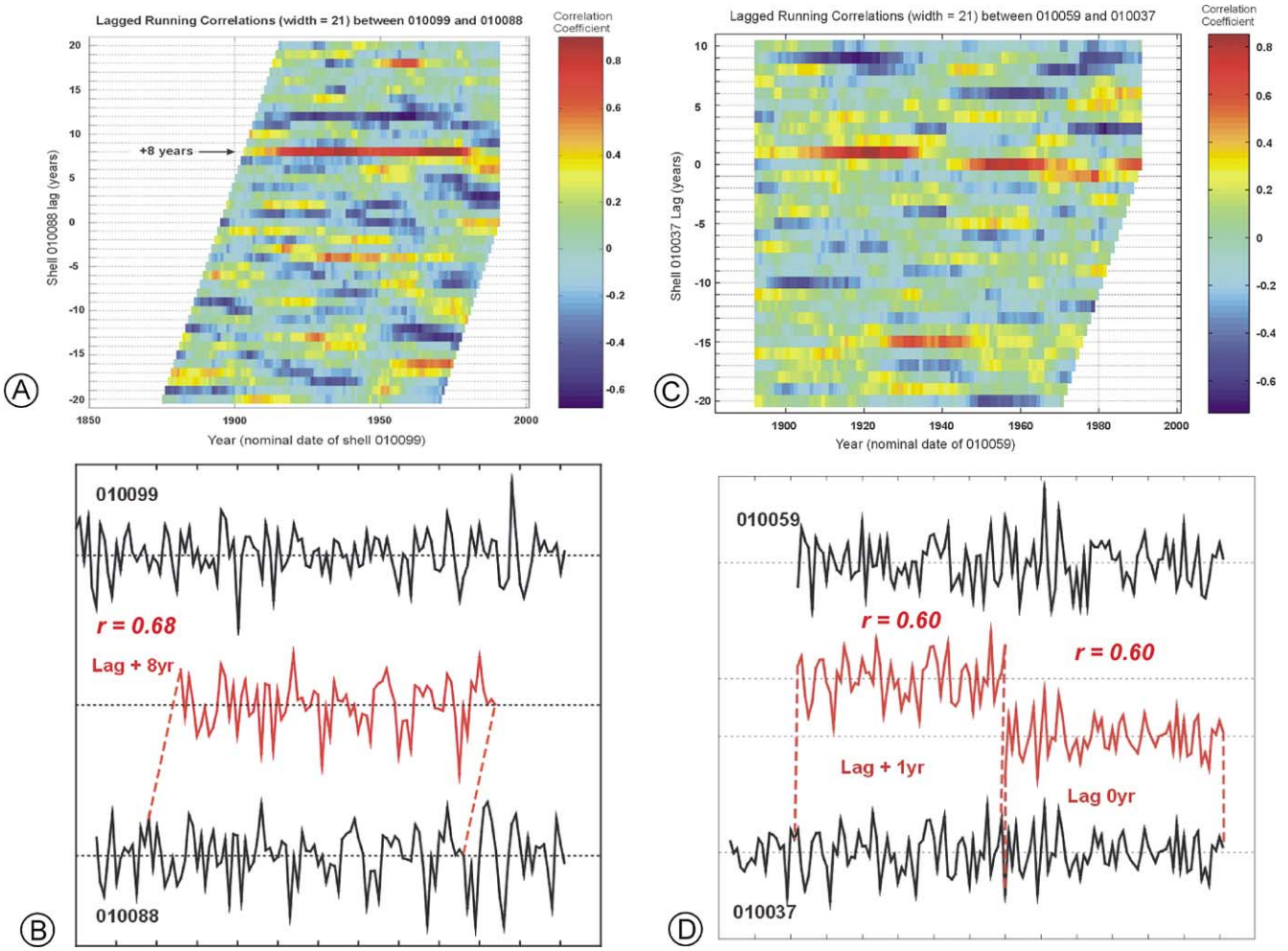



**Figure 5** SHELLCORR graphical output showing lagged running correlations (window width = 21) between growth band series. High positive correlations in red, high negative correlations in blue. (A) Correlation between shells 010088 and 010099 showing best and longest correlation at 8-yr lag. Other high correlations (negative and positive) do appear for other lags but these are neither as strong, nor do they persist for as long, as the 8-yr position. (B) The correlation between the normalized shell growth series for shells 010088 and 010099. The best correlation of +0.68 is achieved if series 010088 is moved forwards by 8 years. (C) Correlation between shells 010059 (120-yr record) and 010037 (145-yr record) (both live-collected in Fladen Ground in 2001 by RV *Scotia* trawl s01 189 in 125 m water depth at 58°47.24′N, 0°20.48′E) showing offset of one year between the two series indicating a missing or double band in one of the series around AD 1940. (D) Normalized growth band series of shells 010059 and 010037. Differently lagged correlations (both +0.6) between the early and late growth series offset by one year demonstrate the power of cross-matching to identify missing or extra bands

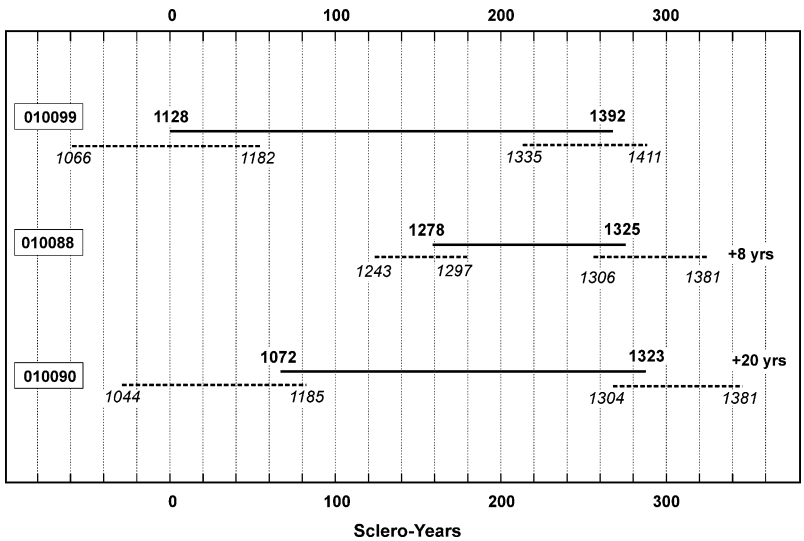



**Figure 6** Length of annual series (sclero-years) of shells 010099, 010088 and 010090 plotted by cross-matched best-lagged correlation fits with reservoir-corrected calibrated ages and 1σ errors (ages (bold) and error bars (dashed) calibrated using the intercept method on the marine calibration curve)

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**Table 1** $^{14}$C data from the *A. islandica* valves from the Fladen Ground used to construct the Mediaeval floating chronology

| AAR-# | Shell number[a] | $^{14}$C age (BP)[b] | Reservoir-corrected $^{14}$C age (BP)[c] | Calibrated $\pm 1\sigma$[d] | $\delta^{13}$C VPDB[e] | $\delta^{18}$O VPDB[e] |
|---|---|---|---|---|---|---|
| AAR-7718 | 010088m | 1041 ± 36 | 641 ± 36 | AD 1325<br>AD 1306–1381 | +2.17 | +3.6 |
| AAR-7719 | 010088u | 1138 ± 36 | 738 ± 36 | AD 1278<br>AD 1243–1297 | +2.41 | +3.74 |
| AAR-7721 | 010090m | 1044 ± 39 | 644 ± 39 | AD 1323<br>AD 1304–1381 | +1.79 | +4.1 |
| AAR-7722 | 010090u | 1309 ± 38 | 909 ± 38 | AD 1072<br>AD 1044–1154 | +2.04 | +3.6 |
| AAR-7732 | 010099u | 1278 ± 38 | 878 ± 38 | AD 1128<br>AD 1066–1182 | +1.56 | +3.45 |
| AAR-7733 | 010099u (loose flake) | 1266 ± 38 | 866 ± 38 | AD 1158<br>AD 1076–1195 | +2.94 | +3.36 |
| AAR-7734 | 010099m | 991 ± 31 | 591 ± 31 | AD 1392<br>AD 1335–1411 | +1.79 | +2.94 |

All samples collected in trawl s01 197 by RV *Scotia* in 2001 in 115 m water depth at 58°49.86′N, 0°21.35′W.
[a] u, umbo; m, margin.
[b] $^{14}$C ages in conventional radiocarbon years BP (before present = 1950) in accordance with international convention.
[c] Reservoir-corrected dates based on reservoir age of 400 years (Harkness, 1983).
[d] Calibration based on the 1998 version 4.0 of the Seattle CALIB program (Stuiver *et al*., 1998) using the marine calibration curve (marine98, $\Delta R = 0$). The intercept of the measured $^{14}$C age with the calibration curve is given in the first line, and this method has been used to calculate the calibrated age interval (second line) corresponding to $\pm 1\sigma$ in the conventional $^{14}$C age.
[e] Isotope measurements quoted with reference to the Pee Dee Belemnite (VPDB) standard.

the cross-matched correlations are significant. The sclero-age for 010099 is 267 years, making it the longest-lived *Arctica* specimen yet reported from the North Sea. The $^{14}$C age for 010099, calculated by subtracting the margin $^{14}$C date from the umbo $^{14}$C date, is 264 years; the umbo date is AD 1128 (1$\sigma$, AD 1066–1182, AAR-7732) and the margin date AD 1392 (1$\sigma$, AD 1335–1411, AAR-7734) (Table 1). The sclero-age start and end dates for all three valves fall within 1$\sigma$ of the respective umbo and margin $^{14}$C ages (Figure 6). The 010099 umbo flake date is consistent with the controlled umbo sample from the same shell valve.

## Discussion

The AMS $^{14}$C results provide a strong and independent indication that the cross-matched shells are contemporaneous. It is therefore concluded that the dendrochronogical method of cross-matching can be applied to correlate fossil *Arctica* growth increment series to construct long absolute time series for the marine environment. Given the analytical errors associated with $^{14}$C dating, and the problem of the variable reservoir effect (eg, Austin *et al*., 1995), it will not be possible to ascribe absolute ages to the Mediaeval floating chronology until it is connected to the series from live-collected specimens by cross-matched shells that complete the hiatus between *c*. AD 1400 and 1790. We believe that we have dated shell material from the Fladen Ground already in hand to enable us to begin to achieve this objective. The dated valves clearly fall into two groups (Figure 7); six reservoir corrected $^{14}$C ages fall in the range 8645 ± 70 (AAR-7729) to 7390 ± 65 (AAR-7735) $^{14}$C BP, and a further 27 fall in the range 32 ± 38 (AAR-7726) to 909 ± 38 (AAR-7722) including the samples from the cross-matched valves described above (Table 1). A further five dead valves gave post-bomb (post-AD 1955) values. This spread of ages demonstrates that (1) early Holocene fossil *Arctica* valves are present in shell lags (residual concentrations of shell) on the floor of the North Sea, and (2) with continued cross-matching of rangefinder-dated valves, the construction of an absolute chronology for the last 1000 years for the North Sea is now feasible. Fossil *Arctica* are common in the Lateglacial glacio-isostatically uplifted marine beds (Clyde Beds, Errol Beds) of Scotland (Peacock, 1989). This raises the possibility that, with further sampling both onshore and offshore in the North Sea region, it may be possible to construct an *Arctica* chronology which extends back some 12 000 years.

It should be emphasized that the accurate and reliable measurement of growth increments from *Arctica* valves is a time-consuming and difficult task. Difficulty arises from the fact that the definition of growth layer boundaries, and their interpretation, can be ambiguous, and short sections consisting of few bands are very easy to mis-date, hence the requirement for long series and statistically rigorous cross-matching. The development of *Arctica* chronologies requires time and extensive support, but the results derived from this study demonstrate that such investment is worthwhile.

## Conclusions

It has been demonstrated in this study that annual growth line series from fossil specimens of the long-lived bivalve mollusc *Arctica islandica* from the northern North Sea can be successfully cross-matched, and the resultant floating chronology independently verified by radiocarbon dating. We present the longest *Arctica* chronology, and the first floating chronology constructed entirely from marine fossils. The cross-matched record covers the period from AD 1000 to AD 1400 and integrates a 267-yr series from the longest-lived specimen yet recorded from the North Sea. These results demonstrate that the construction of a marine sclerochronology, equivalent to dendrochronology in the terrestrial sphere, is now a realistic possibility. The chronology we present differs from existing chronologies in not being time-anchored by the date of collection of live specimens and is therefore a breakthrough because it demonstrates that floating chronologies can be constructed from fossil material. Ultimately these can be linked

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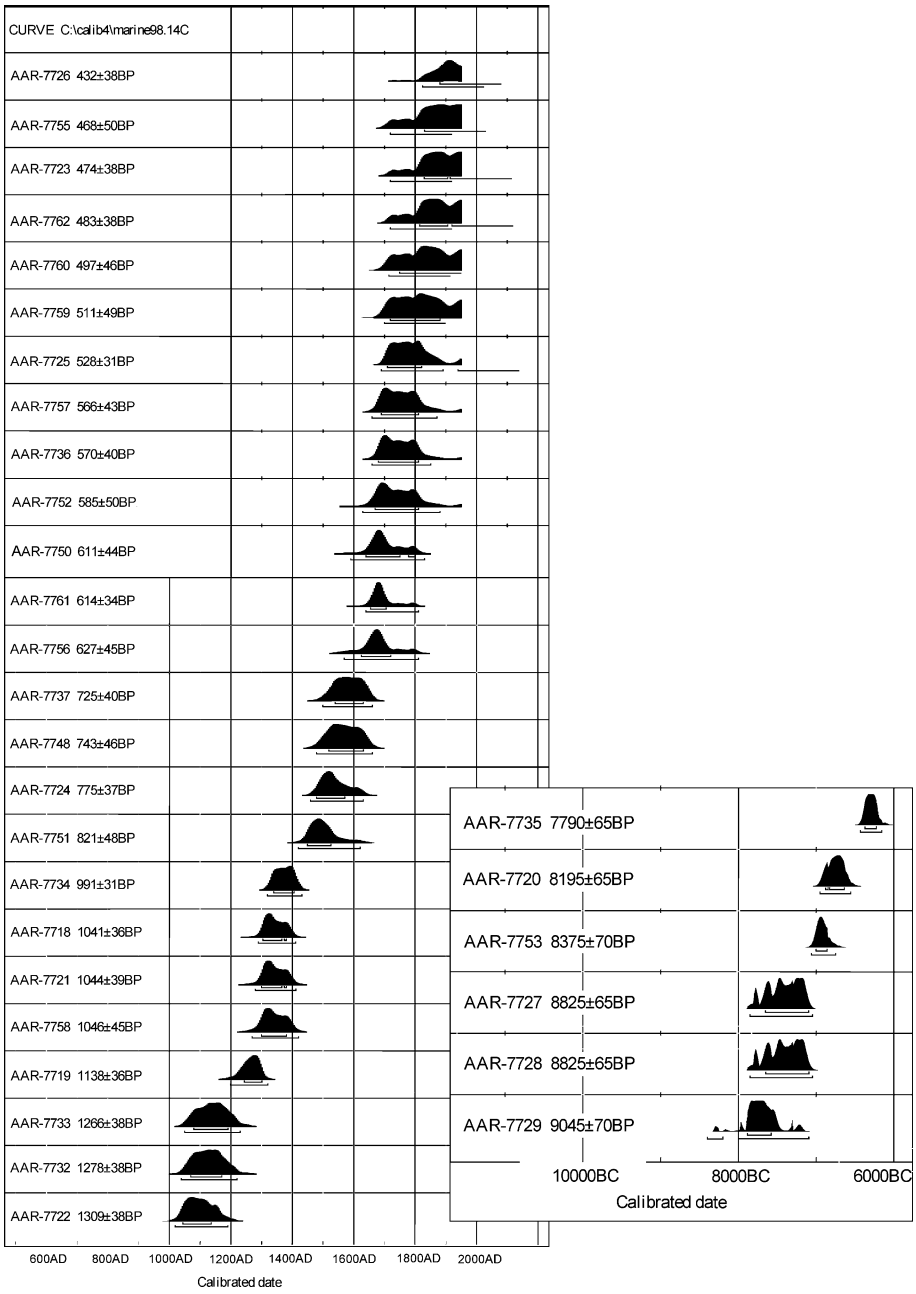



**Figure 7** Calibration plot of all age-sorted $^{14}C$ dated *A. islandica* valves with positive reservoir corrected age from the Fladen Ground, northern North Sea showing probability distributions using the marine model (Stuiver *et al.*, 1998)

and connected to live-based chronologies to provide an absolute timescale for the marine environment.

*Arctica islandica* is distributed widely in the boreal-temperate zone of the North Atlantic, from the Barents Sea to the Gulf of Cadiz, in water depths from 5 to 500 m, and occurs abundantly in some localities characterized by important oceanographic fronts, such as Iceland and the boundary between the Irminger and East Greenland currents. Potentially *Arctica* chronologies could be constructed from across this range of present distribution and into past distributions where fossil specimens exist. Such absolute chronologies will enable significant advances in marine radiocarbon reservoir corrections, water-mass ventilation history, ultra-high-resolution geochemical (trace element concentrations, stable isotopes) proxy records of bottom water temperature and salinity, and constitute a tool for assessing the impact of anthropogenic activity in the shallow marine environment.

However, it should be emphasized that this paper reports only a first step towards achieving these goals. Long chronologies need to be replicated by many overlapping measurement series in order to define the strength of the underlying common forcing signal, which may vary with time, and to calculate the robustness of the chronology. Ultimately, long independent series are required to establish the veracity of the dating scale and their production is likely to take some years, dependent on the availability of long-lived *Arctica* valves.

## Acknowledgements

This study was supported by European Union Fifth Framework HOLSMEER project (EVK2-CT-2000-00060) and the United Kingdom Natural Environment Research Council standard research grant (NER/A/S/2002/00809). We would

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like to thank the Cemlyn Jones Trust for their long and continuing support. We thank Fisheries Research Scotland for permission for GF to collect *Arctica* specimens in the Fladen Ground during a cruise of the RV *Scotia* in 2001, and Brian Long and Paul Butler for help with draughting the figures. Rob Witbaard, Christine Maggs and Nicki Milner are thanked for their constructive comments, which have helped improve the paper.

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