Accurate increment identification and the spatial extent of the common signal in five *Arctica islandica* chronologies from the Fladen Ground, northern North Sea

Paul G. Butler,[1] Christopher A. Richardson,[1] James D. Scourse,[1] Rob Witbaard,[2] Bernd R. Schöne,[3] Nicole M. Fraser,[1] Alan D. Wanamaker Jr.,[1] Charlotte L. Bryant,[4] Ian Harris,[5] and Iain Robertson[6]

[1] The creation of networks of shell-based chronologies which can provide regionally extensive high-resolution proxies for the marine environment depends on the spatial extent of the common environmental signal preserved in the shell banding and on the reliability of the dating model. Here *Arctica islandica* chronologies from five neighboring sites in the North Sea are compared, and the strength of the common environmental signal across distances up to 80 km is analyzed using statistical techniques derived from dendrochronology. The signal is found to be coherent across these distances. In a linked study, chronologies based on one of the same sites but constructed by two different research teams are compared. Methodological differences in increment interpretation are found to lead to slippage in the dating models. Systematic inclusion or exclusion of intermittently occurring increments results in the two chronologies becoming misaligned by 4 years over a 70-year period. Comparisons with neighboring chronologies indicate that such increments can generally be regarded as genuine annual increments even if they are not visible in all shells.

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1. Introduction

[2] A number of recent studies have used the annually deposited growth increments in shells to demonstrate synchronized growth in populations of the bivalve mollusc *Arctica islandica* [*Butler et al.*, 2009; *Helama et al.*, 2006, 2007; *Marchitto et al.*, 2000; *Schöne et al.*, 2002, 2003; *Scourse et al.*, 2006; *Witbaard et al.*, 1997, 2003]. Synchronized growth represents prima facie evidence for the existence of a common environmental signal, that is, a suite of (usually climatic) forcing factors which affects the physical growth of all members of a population in the same way. Such factors may include seawater temperature [*Schöne et al.*, 2005a, 2005b], length of the growing season [*Weidman et al.*, 1994] or food supply [*Witbaard et al.*, 1999]. It has also been possible to link growth and vari-

ability in *A. islandica* with large-scale oceanographic and climatic features, including the hydrography of the northern North Sea [*Witbaard et al.*, 1997] and the winter North Atlantic Oscillation index [*Helama et al.*, 2007; *Schöne et al.*, 2003].

[3] The annual increments in the shell of *A. islandica* are discrete and well defined; in this sense they are similar to tree rings and can be used to fulfill the same function as a high-resolution climate proxy for the marine environment that tree rings fulfill for the terrestrial environment. In addition, the dendrochronological technique of cross-dating can be used to assign absolute calendar dates to dead-collected shells, enabling the proxy archive to be extended back in time before the lifetime of any living animals [*Briffa*, 1995]. In this way, a multicentennial high-resolution archive for the temperate marine environment can be constructed, analogous to the tropical marine archive preserved in coral banding [e.g., *McCulloch et al.*, 1999] and the terrestrial archive in tree rings [*Fritts*, 1976]. In particular, the geographical spread of *A. islandica* populations around the North Atlantic margins [*Dahlgren et al.*, 2000] highlights the utility of the species as a marine proxy in a region of critical importance to the role of ocean circulation as a climate driver [*Keenlyside et al.*, 2008; *Sutton and Hodson*, 2005]. Research into marine paleoclimates is substantially (and for some regions exclusively) based on proxy archives obtained from sediment cores. The dating control of any particular archive is therefore dependent on the accuracy and precision of the age-depth model of the sediment core

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[1]School of Ocean Sciences, College of Natural Sciences, Bangor University, Menai Bridge, UK.

[2]Deparment of Marine Ecology, Royal Netherlands Institute for Sea Research, Den Burg, Netherlands.

[3]Department of Applied and Analytical Paleontology, Institute of Geosciences, Johannes Gutenberg University of Mainz, Mainz, Germany.

[4]NERC Radiocarbon Laboratory, Scottish Enterprise Technology Park, East Kilbride, UK.

[5]Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, UK.

[6]Department of Geography, School of the Environment and Society, Swansea University, Swansea, UK.

from which the proxy was obtained. Age-depth models for Holocene cores are structured around tephra horizons and radiocarbon dates but their accuracy is constrained by uncertainty concerning sedimentation rates, hiatuses, bioturbation [*Anderson*, 2001] and the marine radiocarbon reservoir age [*Eiríksson et al.*, 2004]. The *A. islandica* proxy is complementary to the sediment core record in that it covers the most recent centuries which are often missing from sediment cores because of coring issues or bioturbation, and contributory to it because it can provide a high-resolution record of changes in the marine radiocarbon reservoir age [*Butler et al.*, 2009] which can be used to refine downcore radiocarbon analyses [*Wanamaker et al.*, 2008] and reduce uncertainty in age-depth models.

[4] This paper addresses two key aspects of chronology construction using growth increments in the shell of *A. islandica*: (1) the spatial coherence of the common signal as expressed in contiguous *A. islandica* chronologies and (2) the identification of genuine annual increments, the occurrence of false and missing increments, and the creation of robust and consistent increment-based dating models.

1.1. Spatial Coherence of the Common Signal

[5] If *A. islandica* is to be useful as a proxy archive for synoptic climate in the North Atlantic region, it is important that the consistency of the common signal is maintained across significant distances. Large-scale gridded climate reconstructions using networks of tree ring chronologies require smooth transitions in the signal recorded in neighboring chronologies in order to emulate the regional transitions in the climatic parameters [*Briffa et al.*, 2002]. The common signal recorded in tree rings can be detected across distances as great as 1200 km [*Rolland*, 2002, and references therein]. In the case of the marine environment, the spatial extent of the common signal is likely to be constrained by water mass mixing patterns forced by wind fields, topography and stratification dynamics. Stable frontal systems may impart a strong directional element to the spatial pattern of the common signal so that, for example, the response of molluscs in vertically mixed waters may be very different from the response of the same species in nearby stratified waters [*Schöne*, 2008]. It should be stressed that such locally heterogeneous responses are by no means detrimental to the usefulness of *A. islandica* as a marine paleoproxy, since changes in the degree of similarity of two neighboring chronologies can be used to monitor historic changes in stratification dynamics or regional hydrography, which may in themselves be important indicators of climatic change [*Scourse and Austin*, 2002].

[6] Three recent papers have indicated the potential spatial extent of the common signal in *A. islandica*. *Witbaard et al.* [1997] compared chronologies from two sites 75 km apart in the Fladen Ground (northern North Sea) during the period 1890–1990. The sites showed synchronous response until 1960 but were somewhat negatively correlated thereafter. *Witbaard et al.* [1997] interpreted this switch as a consequence of changes in the hydrography of the Fladen Ground which have affected the food supply to the more northerly of the two sites. The potential of local populations of *A. islandica* to be a proxy for ocean dynamics on a much

larger scale is demonstrated here, since the hydrography of the Fladen Ground is strongly influenced by water mass exchange with the North Atlantic. In another study of *A. islandica* in the North Sea, in this case from a more southerly site on the northern side of the Dogger Bank, *Schöne et al.* [2002] reported that for the period 1950–1995, a single specimen showed synchronous growth with a master chronology which was 200 km distant. *Marchitto et al.* [2000] compared individual shells from five sites on Georges Bank (northwest Atlantic Ocean) separated by distances between 7 km and 48 km and found a trend of decreasing correlation between increment width patterns as distance increased. In this paper five contiguous chronologies close to the Fladen Ground sites identified by *Witbaard et al.* [1997] and separated by distances ranging from zero to 80 km are compared and the extent to which the common signal is expressed across the region and through the common period (1870–1979) covered by the chronologies is analyzed using statistics derived from dendrochronology.

1.2. Identification of Annual Increments

[7] The primary requirement for accurate dating of a chronology is that the increments should be deposited at regular intervals and synchronously throughout a population, and that the deposition interval should be known. The annual nature of increment deposition in *A. islandica* has now been resolved by continuous sampling programs [*Jones*, 1980], mark-recapture experiments [*Murawski et al.*, 1982] and by the identification of a seasonal signal when multiple stable oxygen isotope ratios are measured within a single increment [*Schöne et al.*, 2005a, 2005c; *Weidman et al.*, 1994; *Witbaard et al.*, 1994], and synchronous growth in populations has been demonstrated by the successful construction of increment width chronologies [*Butler et al.*, 2009; *Helama et al.*, 2006; *Schöne et al.*, 2003; *Witbaard et al.*, 1997]. It has not yet been established that increments in shallow water (<25 m) populations of *A. islandica* are always deposited synchronously or annually [*Epplé et al.*, 2006; *Turekian et al.*, 1982]; such populations may be more vulnerable to external disturbances such as storm action or variable salinity which can result in subannual growth checks [*Richardson*, 2001, p. 105].

[8] Although the annual and synchronous nature of increment deposition outside very shallow waters has been established, there is as yet no standard method for dealing with cases where increments do not appear in all members of a population. In tree ring research, missing or false rings are generally identified (1) by comparing many tree ring series from the same population [*Douglass*, 1934], (2) by anchoring them to wood of a known date obtained from an archeological site [*Douglass*, 1934] or (3) by comparison with a neighboring, similar, population [*Fritts*, 1976]. At this stage in the development of shell-based chronologies, only the first approach is generally available (the second approach being available only to a very limited extent). The third approach is precluded because the few shell-based chronologies that have so far been constructed are isolated in space. In practice, the causes of false or missing increments are likely to be local, so that when networks of shell-based chronologies have been developed, the alignment of unambiguous increment width

patterns across multiple chronologies can be used to identify the anomalous increments. The equivalent to the second approach for shell-based chronologies is the identification of historic specimens of *A. islandica* with a known date of death. These can sometimes be obtained from museum collections, although such shells are more likely to have originated in very shallow waters than in the deeper populations from which most chronologies have been constructed. Those specimens which are available, for example those used by *Schöne et al.* [2005b], are very rarely dated earlier than the beginning of the twentieth century, and can therefore only be used to verify increment identification during the past 100 years. The first approach, comparison of increment width patterns within a population, can lend consistency to an increment identification methodology, but in the absence of any independent verification it cannot guarantee accuracy. If the methodology incorporates a bias toward including or excluding increments which occur intermittently in the population, cumulative slippage is likely to occur, potentially leading to quite significant dating errors propagating through the chronology.

[9] This paper addresses the issue of increment identification in *A. islandica* with a specific example. Two independent chronologies for the same site in the Fladen Ground, northern North Sea are compared and are found to diverge back through the twentieth century so that by 1900 equivalent increments are separated by 4 years. Specific increments which are treated differently in the two chronologies are identified and illustrated. The determination of the correct interpretation of the increments is approached (1) by comparing the chronologies with increment width patterns from a shell from a museum collection with an assigned date of death in March 1905 and (2) by investigating the expression of the equivalent increments in neighboring chronologies from the Fladen Ground.

2. Materials and Methods

2.1. Collection of Shell Material

[10] Dead shells and living specimens of *A. islandica* were collected from the seabed at four sites in the Fladen Ground, northern North Sea, during cruises of the R/V *Scotia* in May and June 2001 and of the R/V *Prince Madog* in June 2004. Fishing gear during the 2001 cruise was a standard *Nephrops* otter trawl and for the 2004 cruise it was a heavy, toothed dredge, customized for the collection of live specimens and dead shells of mature *A. islandica*. Site IDs, positions and depths were: site A (58°49.8′N, 0°20.5′W, water depth 115 m); site B (59°7.4′N, 0°9.9′E, water depth 125 m); site C (58°47.2′N, 0°20.5′E, water depth 150 m); and site F (59°23.1′N, 0°31.0′E, water depth 130 m). Figure 1 (adapted from *Turrell et al.* [1996]) shows the positions of the four sites, the regional hydrography and the 100 and 200 m depth contours.

[11] After collection, live-collected *A. islandica* were labeled and frozen. Dead-collected shells were scrubbed to remove encrustations, air-dried and labeled. In the laboratory the live-collected specimens were thawed, the flesh removed and the shells washed and air-dried. For all shells, the shell length (anterior-posterior axis), shell height

(height along maximum growth axis), shell width and condition indicators (periostracum preservation, condition of the outer shell rim, ligament condition, degree of bio-erosion and boring and nacre condition) were recorded.

2.2. Shell Processing

[12] The standard shell preparation technique is described in detail by *Scourse et al.* [2006] and *Butler et al.* [2009]. In summary, the shell is sectioned along its axis of maximum growth to expose growth increments in the hinge plate and in the shell margin. The sectioned surface is then ground using carborundum paper, polished with diamond paste and acid etched for 120 s in 0.1M HCl. An acetate peel replica of the etched surface is created and mounted on a labeled microscope slide so that it can be viewed under transmitted light at various magnifications and the growth increment widths can be measured using image processing software.

[13] In any single individual, equivalent growth increment series may be found in the tooth/hinge plate region and in the shell margin of both valves, a total of four positions altogether. In order to maximize replication and minimize errors due to within-animal variability, it is usually recommended that shell-based chronologies should be constructed using measurements from different parts of the shell [*Butler et al.*, 2009]. For this study, however, the margin was not available for all shells, and to maximize consistency of treatment when comparing chronologies from several sites, most of the measurements were made in the hinge region. In a very few cases, where the increments in the hinge were clustered closely together and could not be measured with sufficient precision, the equivalent increments were measured in the margin and rescaled.

2.3. AMS Radiocarbon Dating

[14] AMS radiocarbon dating, carried out on samples taken from the outer (most recently deposited) edge of dead-collected shells, was used to constrain the position of the shells within the developing chronology and to minimize the possibility of a random but spurious match being accepted [*Butler et al.*, 2009]. In order to accommodate the amount of material required for AMS dating, it was necessary to submit samples which integrated the final years of growth. It was not possible to be precise about the number of years integrated, since this was dependent on the size of the shell and the precise point on the outer edge from which the sample was cut, but a figure of 40 years is used here as a working approximation. Shells were selected for radiocarbon dating on the basis of size (larger shells were expected to be the longest lived) and taphonomic characteristics that suggested that they might have been alive during the past millennium and were submitted to the NERC Radiocarbon Laboratory (East Kilbride, United Kingdom) or to the AMS ^{14}C Dating Centre (University of Aarhus, Denmark).

2.4. Chronology Construction

[15] Increment width series in *A. islandica* are characterized by strong growth trends, with wide increments during the fast growing juvenile phase, rapidly decreasing widths in adolescence and early maturity (typically up to 60 years) and narrow increments thereafter [*Helama et al.*, 2006;
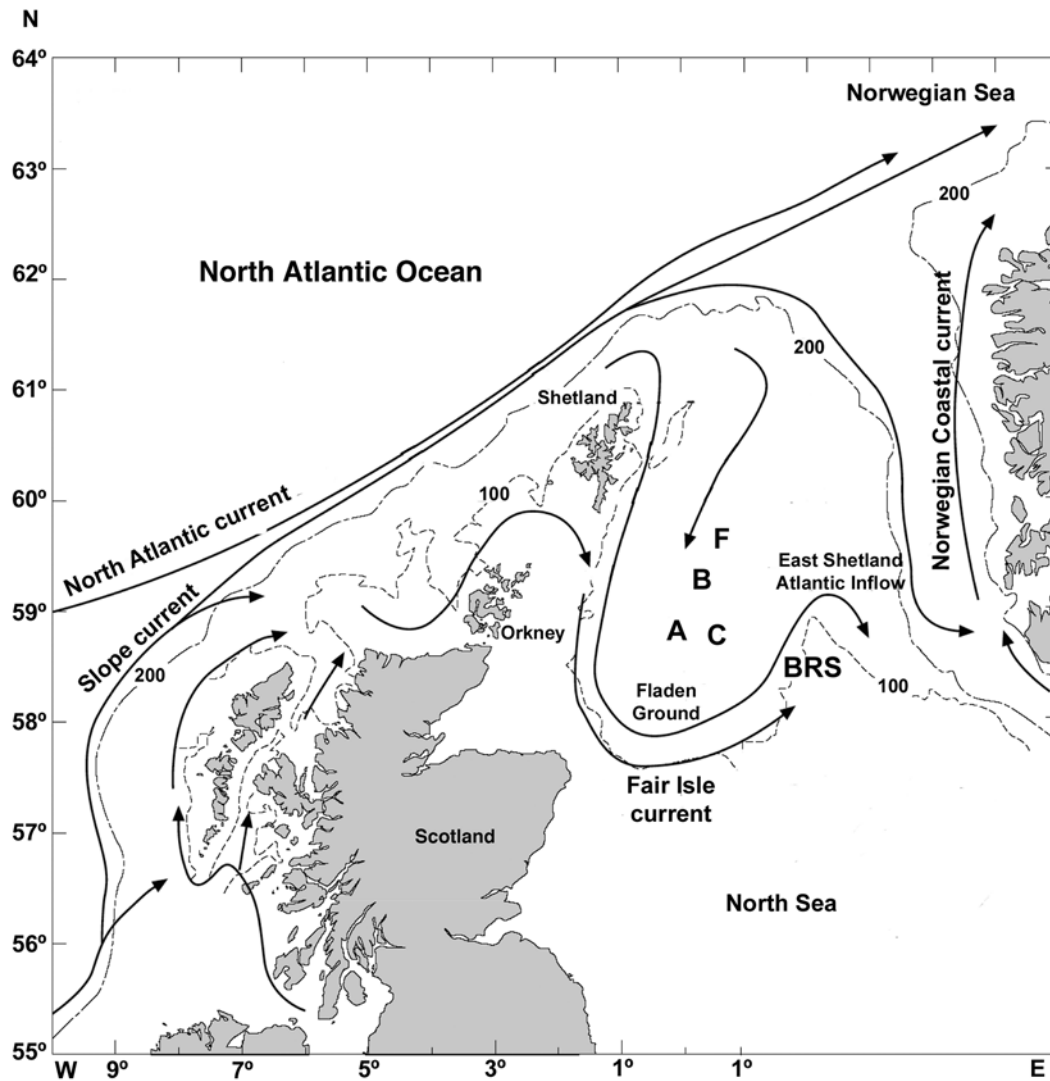
Figure 1.   The northern North Sea, showing the four sites (A, B, C, and F) of the five chronologies used in this study. BRS shows the collection site of shell BRS (section 3.3.2). The regional hydrographic regime and the 100 and 200 m depth contours are also shown. The image is adapted from *Turrell et al.* [1996] by permission of *Turrell et al.* [1996] and Oxford University Press.

Schöne et al., 2004; *Scourse et al.*, 2006]. A similar trend affects the variance of the increment widths, the standard deviation being roughly proportional to the mean. It is necessary to remove these trends before a chronology can be constructed, since chronology construction using a mean value function of several increment width series requires that the series being averaged are statistically stationary (that is, they possess a common mean and stable variance [*Cook et al.*, 1990a, pp. 104–105]). Since tree ring series have similar trends in mean and variance, statistical methods developed by dendrochronologists are used to detrend the *A. islandica* increment width series.

[16]   There are three principle stages in the construction of a shell-based chronology: (1) the selection and dating of increment width series to be included in the chronology, (2) the creation of time series of standardized growth indices (SGIs) by detrending the individual series and (3) the

creation of chronology SGIs by applying a mean value function to the individual SGIs. The series to be included in each chronology were initially determined by correlating them with one another after they had been detrended with a high-pass filter. Series from live-collected animals were provisionally dated by assigning the outermost complete increment to the year before collection and counting back increments (Figure 2). Series from dead shells were then cross-dated [*Pilcher*, 1990; *Wigley et al.*, 1987] with the live-collected series. At all stages cross-dating was verified by visual inspection [*Baillie*, 1982].

[17]   Using the cross-dated increment width series, chronologies were constructed with the standard dendrochronology software package ARSTAN [*Cook and Holmes*, 1996; *Cook and Krusic*, 2007]. The trend in variance was stabilized by applying a data adaptive power transformation [*Cook and Peters*, 1997] to the raw measurements from each series, and
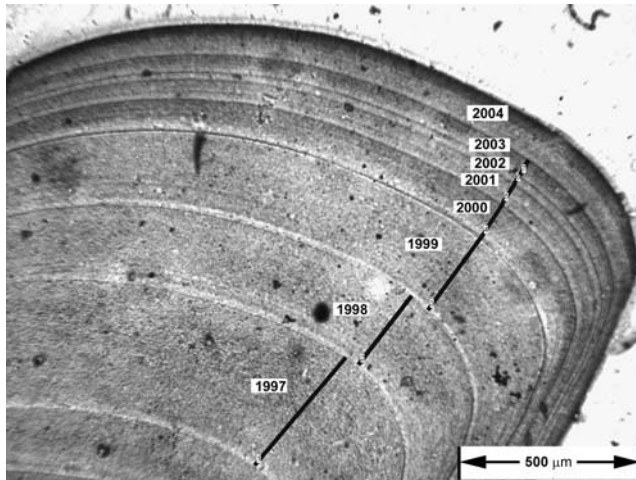
Figure 2. Photomicrograph of an acetate peel image taken from the hinge plate of an *Arctica islandica* shell (0401406L) collected from the Fladen Ground, northern North Sea in June 2004. Measured increments are indicated by thick black lines. The outermost increment is incomplete and was growing in the year of collection. Other increments are dated sequentially back in time.

the trend in mean was removed with a flexible 15-year spline. Since the purpose of this study is to assess synchronicity of response within and between chronologies, rather than to study the chronology response to external factors such as climate, the removal of low-frequency variability with a flexible spline is appropriate. Any low-frequency variability (including the growth curve but also including low-frequency climate signals) will tend to bias comparisons within and between chronologies in favor of strong correlations if the trends are coeval and against them if they are dispersed in time. The SGIs were derived for each series by subtracting the transformed raw increment widths from the spline. Finally, the chronology SGIs were formed by using a biweight robust mean function [*Cook et al.*, 1990b] of the individual series SGIs.

2.5. Comparison Between Chronologies

[18] In order to examine the spatial coherence of the shell growth response, five chronologies were constructed for four sites in the Fladen Ground (Figure 1). One chronology was constructed for each of sites A, B and C and two separate chronologies (designated F1 and F5) were constructed for site F using shells collected in different tows. Each chronology consisted of five increment width series, each series being from different animals. In order to standardize as far as possible the period covered by all the chronologies, the increment width series were truncated where possible to the period 1870–1979 (Table 1). The separation between the sites varies between 40 km (A and C) and 82 km (F and C).

[19] Statistical tests commonly used in dendrochronology were used to assess the strength of the common response within each chronology and the coherence of the response between the chronologies.

[20] 1. The Gleichläufigkeit (GLK), or sign test, is the percentage of years in which the increment widths in two series being compared increase or decrease in synchrony [*Fritts*, 1976; *Schweingruber*, 1988]. This method detects only high-frequency changes and takes no account of the relative or absolute magnitudes of the increment widths. A value of 50% indicates no correspondence between two series, whereas values above 65% are usually considered to be highly significant.

[21] 2. The correlation coefficient, r, is the conventional Pearson correlation coefficient between the two increment width series after detrending as described in section 2.4.

[22] 3. The Baillie-Pilcher t value (t_{BP}) is a version of the Student's t test. As such, it provides an indication of the probability that the correlation between two time series has arisen by chance. t_{BP} is calculated as

$$t_{BP} = (r_{BP} * \sqrt{(N-2)})/\sqrt{(1 - r_{BP}^2)}$$

where N is the number of years of overlap between the two series and r_{BP} is the correlation coefficient of the two series after they have been detrended and normalized as described by *Baillie and Pilcher* [1973]. Application of standard Student's t significance levels to these results is not justified because even after detrending increment width series are usually autocorrelated, but in dendrochronology values of t_{BP} greater than about 6.0 for ring width series longer than 60 years indicate that a statistically significant correlation has been identified [*Pilcher et al.*, 1995]. Where multiple series indicate mutually consistent matches, values of t_{BP} greater than 3.5 are often considered acceptable [*Miles*, 1997].

[23] 4. Expressed population signal (EPS) is a criterion for the fidelity with which a chronology constructed using increment widths from a sample of a population expresses the common environmental forcing in the whole population [*Briffa and Jones*, 1990; *Wigley et al.*, 1984]. EPS is a function of the number of increment width series used in the chronology and the strength of the correlations between them. The simpler form of the EPS calculation, which assumes that the chronology is made up of one series per animal, is

$$EPS = (n * \text{Rbar})/(n * \text{Rbar} + (1 - \text{Rbar}))$$

where n is the number of series and Rbar is the mean correlation between the detrended series. A high EPS indicates a strong common forcing in the population. *Wigley et al.* [1984] suggest as a guide that a reasonably representative chronology should have an EPS around 0.85. With EPS around this value or higher, any additional error due to the use of a sample of the population would not significantly impact the explanatory power of the chronology.

[24] GLK, r and t_{BP} are used to compare pairs of individual increment width series within chronologies and to compare the chronologies with each other, while EPS is used to assess the development of chronology strength through time. Where a statistic refers to an individual

Table 1. Details of the Shells Included in Chronologies A, B, C, F1, and F5

Shell ID[a]	Full Lifetime[b]	Years in Chronology[c]	Collection Date or Date Range From [14]C Analysis[d]	[14]C Analysis Sample ID[e]
		A		
010097L	1867–1981	1870–1979	[14]C modern	AAR-7730
010644L	1889–1972	1889–1972	[14]C modern	SUERC-3270
010647L	1830–1965	1870–1965	1900–1930	SUERC-3276
010652R	1835–1970	1870–1970	1900–1930	SUERC-3281
0400147L	1891–1977	1891–1977	[14]C modern	SUERC-4983
		B		
0401246L	1867–2004	1870–1979	Collected live, 2004	
0401254L	1856–2004	1870–1979	Collected live, 2004	
0401258L	1856–2004	1870–1979	Collected live, 2004	
0401260L	1755–2004	1870–1979	Collected live, 2004	
0401262L	1850–2004	1870–1979	Collected live, 2004	
		C		
010629L	1852–1989	1870–1979	[14]C modern	SUERC-3249
010635L	1853–1994	1870–1979	[14]C modern	SUERC-3258
010721L	1856–1984	1870–1979	[14]C modern	SUERC-8463
010725L	1758–1993	1870–1979	[14]C modern	SUERC-8470
010729L	1865–1991	1870–1979	[14]C modern	SUERC-8476
		F1		
0401422L	1874–2004	1874–1979	Collected live, 2004	
0401423L	1908–2004	1908–1979	Collected live, 2004	
0401424L	1869–2004	1875–1979	Collected live, 2004	
0401431R	1885–2004	1885–1979	Collected live, 2004	
0401445L	1848–2004	1870–1979	Collected live, 2004	
		F5		
0401381R	1865–2004	1870–1979	Collected live, 2004	
0401391L	1885–2004	1885–1979	Collected live, 2004	
0401403L	1865–2004	1870–1979	Collected live, 2004	
0401409L	1860–2004	1870–1979	Collected live, 2004	
0401412L	1870–2004	1871–1979	Collected live, 2004	

[a]L and R indicate left and right shell valves, respectively.
[b]Full lifetime of each shell as determined from the chronology dating model.
[c]Subset of full lifetime used in the chronology to give best coverage of the years 1870–1979.
[d]Independent determination of the date of death shown by year of collection if the specimen was collected alive or from ^{14}C analysis of dead shells. For prebomb pulse shells, the calibrated dates shown are 1σ ranges calculated using OxCal version 4.0 [*Bronk Ramsey*, 1995, 2001] with the Marine04 calibration curve [*Hughen et al.*, 2004] and $\Delta R = 20 \pm 42$ [14]C years [*Mangerud and Gulliksen*, 1975]. The sample ^{14}C ages were 352 ± 35 and 193 ± 35 ^{14}C years B.P. for 010647L and 010652R, respectively.
[e]AAR indicates ^{14}C analysis carried out at AMS [14]C Dating Centre, University of Aarhus, Denmark; SUERC indicates NERC Radiocarbon Laboratory, East Kilbride, United Kingdom.

chronology, the statistic will be subscripted, e.g., A_{EPS}. The values of GLK, r and t_{BP} were obtained from Rinntech TSAP-Win Professional Version 0.59 [*Rinn*, 2003]. Values of EPS were obtained from the standard dendrochronology program ARSTAN for WINDOWS version 41b [*Cook and Krusic*, 2007].

2.6. Construction of *Witbaard et al.* [1997] Chronology

[25] For assessment of the variability between chronologies attributable to different working methods, a version of the F5 chronology (adapted with the addition of one series and extended forward to 2000; this version is described hereafter as FB) was compared with a chronology constructed for the same site by *Witbaard et al.* [1997] (hereinafter referred to as FW). The shell preparation and chronology construction methodologies used by *Witbaard et al.* [1997] differ in some respects from those described in sections 2.2 and 2.4: (1) the increments were measured on the shell margin rather than in the hinge plate; (2) a fixed

logarithmic transformation rather than a data adaptive power transformation was used to stabilize the variance; (3) for the final detrending a logarithmic curve was fitted to the transformed increment widths rather than a negative exponential curve; (4) the series SGIs were created using division rather than subtraction; and (5) in order to reduce intrashell variability and enhance the strength of the common signal in the chronology, each shell was measured along two or three transects rather than one.

2.7. Comparison With *Witbaard et al.* [1997] Chronology

[26] FB and FW were compared using the visual correlation tool SHELLCORR which shows running correlations at different lags so that the locations of possible mismatches are visible as points at which a strong correlation shifts from one lag to another (see sections 3.2 and 3.3 below). The peel images of the growth increments were studied to find possible missing or false increments, in particular incre-
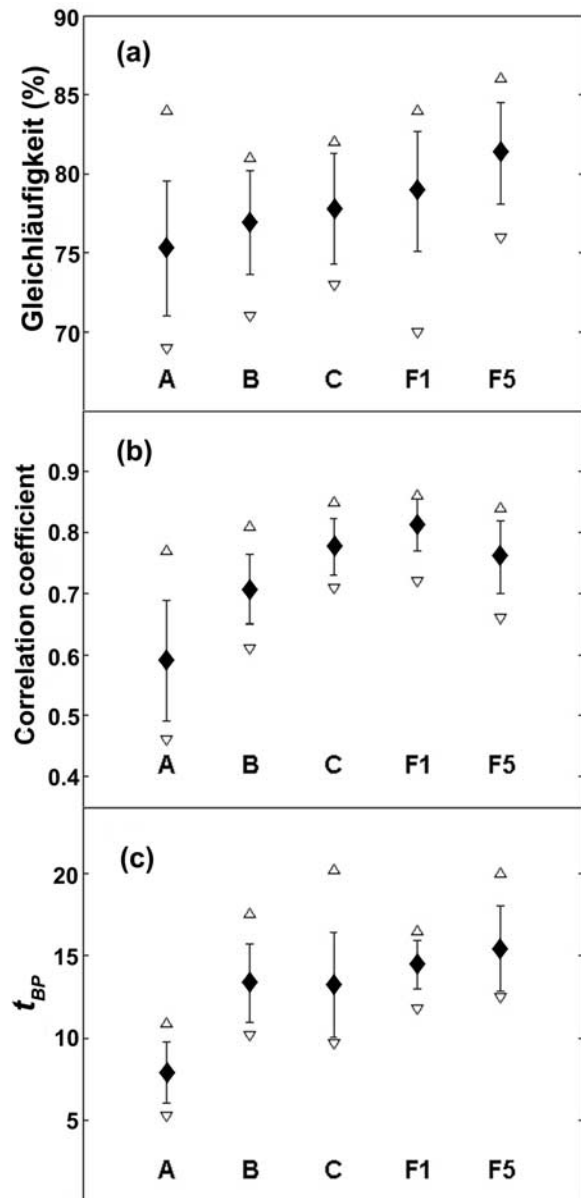
Figure 3. (a) Gleichläufigkeit, (b) Pearson correlation coefficient, and (c) Baillie-Pilcher *t* value for pairs of shell increment width series used in five chronologies from the Fladen Ground, northern North Sea. For each chronology (A, B, C, F1, and F5), diamonds, mean value; triangles, maximum; inverted triangles, minimum. Error bars show standard deviation.

ments which were not present in all the shells used in the chronology. The presence, partial absence or absence of such increments was determined for 17 shells, and FB was adjusted to align it with FW. The possibility of independent verification of the dating model was considered and measurements from a single shell with a known date of death in 1905 were compared with FB and FW. Finally, presence/absence of the intermittently occurring increments over a

wider spatial range was investigated by studying their expression in chronologies A, B and C.

3. Results

3.1. Coherence of Individual Series Within Each Chronology

[27] Gleichläufigkeit (GLK), correlation coefficients (r) and Baillie-Pilcher t values (t_{BP}) are shown in Figures 3a–3c. For each chronology, the mean (diamonds), standard deviation (error bars), maximum (triangles) and minimum (inverted triangles) values of each statistic are shown for 10 pairs of increment width series. By all three criteria, the correspondence between the series in chronology A is noticeably lower than it is for the other four chronologies. For t_{BP} it is quite considerably lower. Correspondences between series in the four chronologies excluding A are similar, showing no geographical trend.

[28] EPS is shown in a 30-year rolling window in Figure 4 for four of the five chronologies (to assist clarity $F1_{EPS}$ is not shown because it is undefined before 1905 and very similar to C and F5 thereafter). EPS is a function of the number of series in the chronology at any particular time (sample depth) and the strength of the correlations between the same series (see section 2.5). Where sample depth is constant (as is the case for B and C) EPS can be expected to mirror directly the relationship between correlation coefficients shown in Figure 3b, and in Figure 4 it is clear that C_{EPS} remains above B_{EPS} throughout the study period. If sample depth is reduced at the start of the period (see entries for A and F5 in Table 1), there is a proportionate effect on EPS, so that $F5_{EPS}$ is clearly affected by the loss of just one series and A_{EPS} is significantly affected by the loss of two series. $F1_{EPS}$ is not defined prior to 1905 because its sample depth is reduced to one series. Even for B and C, however, EPS is reduced at the start of the period, possibly indicating
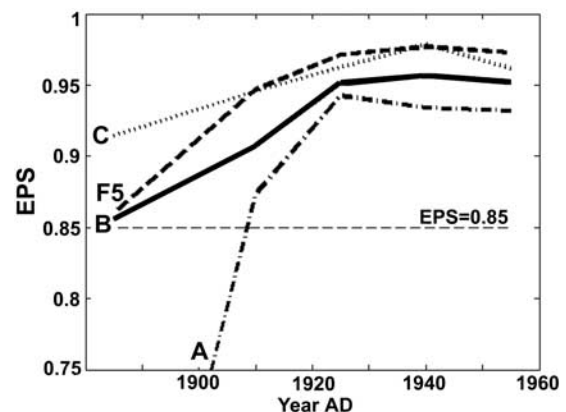

Figure 4. Expressed population signal (EPS) for A (dot-dashed), B (solid), C (dotted), and F5 (dashed) calculated in a 30 year rolling window. To assist clarity, A_{EPS} for 1885 (0.48) and all values of $F1_{EPS}$ are not shown. $F1_{EPS}$ is not defined before 1905 and is very close to $F5_{EPS}$ and C_{EPS} thereafter. The horizontal dashed line shows the suggested threshold value of EPS [*Wigley et al.*, 1984].
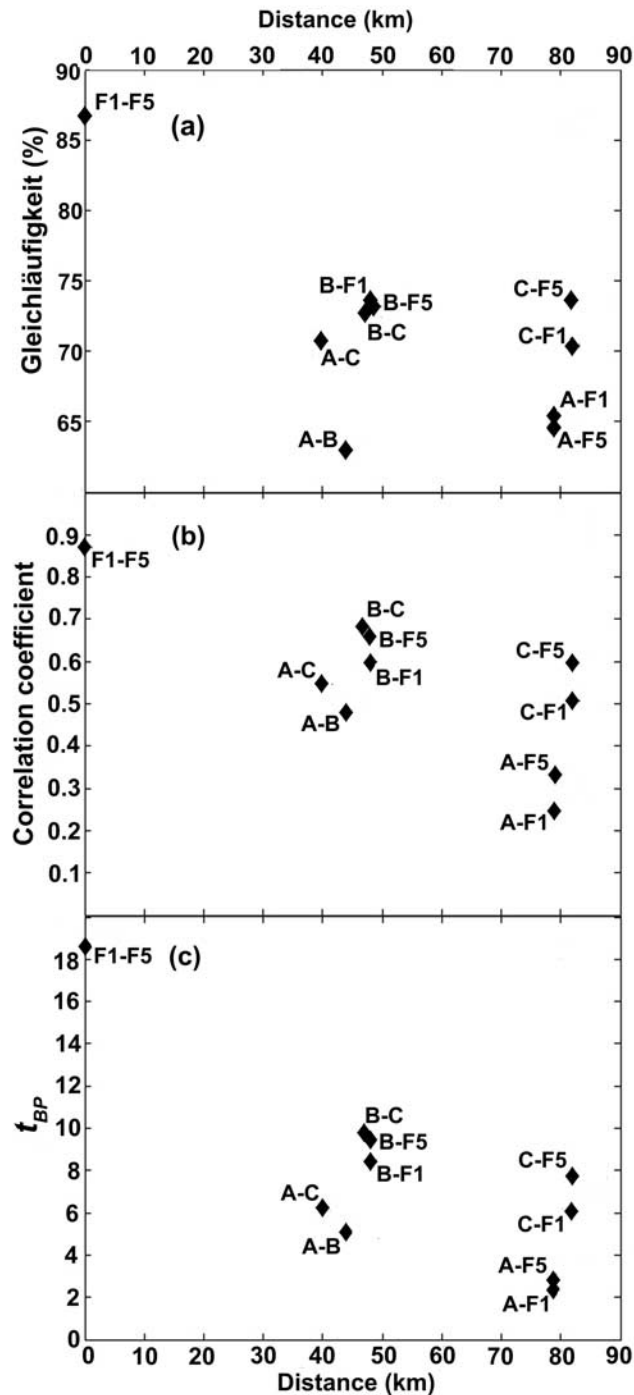
Figure 5. (a) Gleichläufigkeit, (b) Pearson correlation coefficient, and (c) Baillie-Pilcher *t* value plotted against distance for each pair of chronologies from the Fladen Ground, northern North Sea.

an enhanced influence of life effects on shell growth during the juvenile years.

3.2. Spatial Coherence of the Chronologies

[29] Figures 5a–5c show GLK, *r* and t_{BP} for all pairs of chronologies plotted against the distance between the chro-

nologies. Negative trends are evident for all the statistics, with correspondences becoming weaker as the distance between the chronologies increases. For the GLK alone, there appears to be little or no negative trend at distances greater than 40 km. In all cases, pairs which include the A chronology plot below the other pairs, reflecting the relatively poor correlations between the series used to construct it. The development through time in the correlations between chronologies is shown in Figures 6a–6j. The SHELLCORR images show the color coded correlation coefficients between each pair of chronology indices in a 13-year running window. Where strong positive correlations are shown at zero offset, it can be assumed that the dates allocated to the indices are correct for both chronologies. To show the possible occurrence of mismatches, correlations are also shown where the indices have been offset by 1 year with respect to each other. For example, in Figure 6a the top (bottom) row shows the correlation between A and the previous (following) year's value of B. See *Scourse et al.* [2006] for a more detailed explanation of the interpretation of SHELLCORR images.

3.3. Comparison Between Chronologies FB and FW

[30] Lagged correlations between FB and FW are shown in the SHELLCORR image in Figure 7. Apart from obvious points of mismatch where periods of strong correlation are offset by 1 year, the two chronologies are well correlated, an indication that the expression of the common signal in *A. islandica* growth increments is largely independent of (1) the actual shells used, (2) the processing techniques, (3) the part of the shell measured (i.e., shell margin or hinge plate) and (4) the specific groups which carried out the research. The differences that may be attributable to some or all of these factors can be seen in the stronger correlation shown in Figure 6j between two chronologies from site F which were processed at a single institution (School of Ocean Sciences, Bangor) using identical methods. The stepwise shifts in the offset shown in Figure 7 demonstrate clearly that FB and FW diverge at four discrete points: in the 1960s, twice in the 1930s/1940s and again in the early 1920s. Each point of divergence represents an increment which has been included in FB but not in FW. The observation that the direction of divergence is consistent is an indication that the shifts may result from methodological differences rather than from ad hoc decisions about individual increments.

3.3.1. Doubtful Increments

[31] It is reasonable to proceed on the assumption that increments which were included in FB but not in FW were absent in at least some, if not all, of the increment width series used in FW, and that most likely they were absent in some of the series used in FB. If such doubtful increments are evident at points of divergence between the two chronologies, they can be removed from FB or added to FW in order to align the chronologies. In addition to the six shells used in FB, 11 further shells from site F were selected for study (on the basis that their increments were reasonably strongly expressed in photomicrographs of their peels) in order to identify precisely the position and presence or absence of particular doubtful increments. Some of the
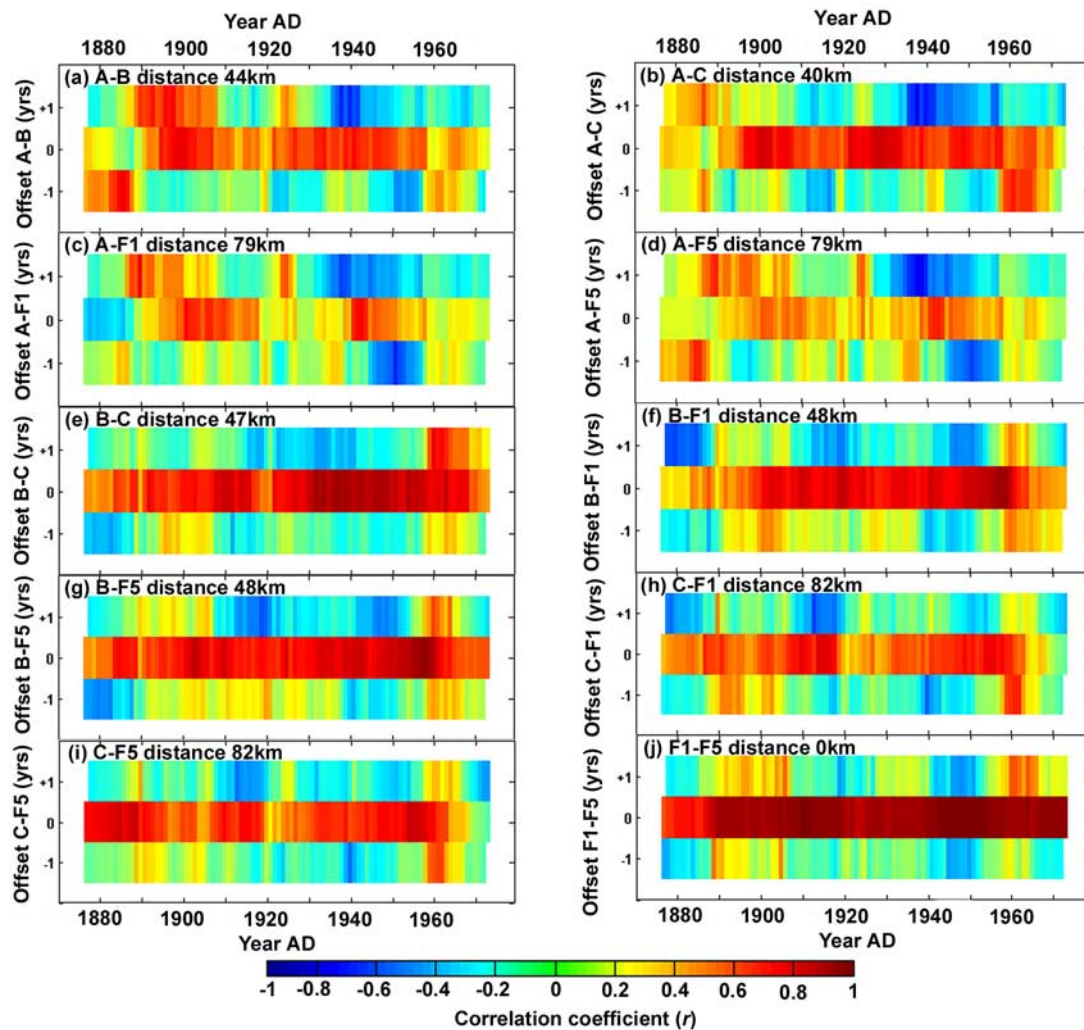
Figure 6. (a–j) SHELLCORR images showing the correlation coefficients between pairs of chronology indices in a 13-year running window. Positive correlations are red, and negative correlations are blue as shown in the color bar. Correlations are shown at the correct offset (offset = 0) and also where the indices have been offset by 1 year with respect to each other. For example, in Figure 6a the top (bottom) row shows the correlation between A and the previous (following) year's value of B.

photomicrographs are shown here (Figures 8, 9, and 10) to demonstrate the variability with which such increments may be expressed in the shell. Increments are identified by their number on the image or by calendar year as initially assigned in FB. In order to emphasize that the dates are provisional, calendar years are shown in quotes (e.g., "1969"). Although only a limited number of increments can be shown in the images, signature years (individual wide or narrow increments or characteristic groups) are used to contextualize the target increment. These patterns are almost always present (a precondition for the periods of strong correlation shown in Figure 6) and can reliably be used to identify precise periods on the image.

3.3.1.1. Year "1969"

[32] Figure 8 shows parts of the magnified peels from shell 0401423L (Figure 8a) and shell 0401436L (Figure 8b). Signature years that the images have in common are the three narrow increments at the bottom of each image (increments 2, 3, and 4 which are equivalent to "1959," "1960" and "1961") and the wide increment at the top (increment 14, equivalent to "1971"). Here "1969" is present in Figure 8a as a narrow increment (12), marked by arrows, but not in Figure 8b where it has been inserted as increment 12.

3.3.1.2. Years "1937," "1945," and "1947"

[33] Figure 9 shows equivalent parts of the peels from shell 0401423L (Figure 9a) and shell 0401409L (Figure 9b). The signature years for this sequence start with the relatively wide year "1936" (increment 5) and end with the wide-narrow-wide sequence from "1949" to "1951" (increments 18, 19, and 20). 0401423L has a more recent settlement date ("1909") than most of the shells included in FB, and the increments for this relatively juvenile period are therefore wider than they are in the other shells. In this case
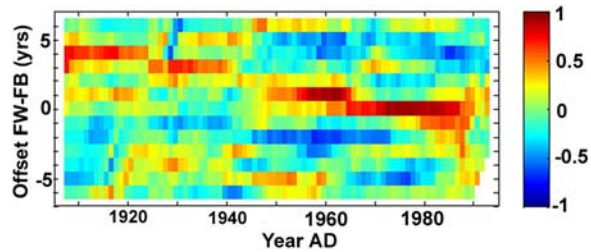
Figure 7. Correlation coefficients between FB and FW shown in a 13-year moving window and at offsets from −6 to +6. Note the prominent stepwise shift to a positive 4 year offset of FW from FB. Each shift to a larger offset represents a point at which an increment is included in FB but not in FW.

the years "1937," "1945" and "1947" (marked with black arrows) are narrower than the other increments, but they are nevertheless clear and unambiguous. In the case of shell 0401409L, whose settlement date was "1858," the animal was more mature during the period shown on the image, and the increments are narrow compared with those for 0401423L (for example, the wide increment for "1936" (5) is 175 μm in 0401423L and 28 μm in 0401409L). "1937" and "1945" are missing from the image of 0401409L (inserted as increments 6 and 14), and "1947" is extremely thin (increment 16).

3.3.1.3. Year "1923"

[34] Photomicrographs of peels showing increments from three shells during the period around "1923" are shown in Figure 10. The signature years at this time are the wide increments for "1915" and "1927." These are shown as increments 1 and 13 (although for reasons of space incre-

ment 1 is not included in Figure 10a). As before, the relatively juvenile shell 0401423L shows "1923" prominently and clearly (increment 9 in Figure 10a). In shell 0401409L (Figure 10b), the two lines which delimit "1923" are extremely close together and occasionally appear to merge into one slightly thicker line. In shell 0401391L (Figure 10c), "1923" is missing, and has been inserted as increment 9.

3.3.1.4. Assessment of Doubtful Increments in 17 Shells

[35] The presence/absence of the five doubtful increments was assessed in 17 shells, with the results shown in Table 2. Reference to Figure 7, which indicates the positions of mismatches between FB and FW suggests that they can be aligned if "1923," "1969" and any two of "1937," "1945" and "1947" are removed from FB. The results shown in Table 2 indicate that "1923" and "1969" are clearly visible in only a small minority of shells and might reasonably be regarded as false increments and that "1947," which is visible in most of the shells, has the best case of the five to be viewed as a genuine annual increment. "1937" and "1945" which appear unambiguously in slightly more than half of the shells and are missing in about 25%, are more problematic. However, the present state of knowledge of growth increment formation in these marginal cases does not support a decision to include or remove these or, indeed, any of the five increments. If the goal is to align FB and FW, the removal of "1923," "1937," "1945" and "1969" from FB would be one, albeit arbitrary, approach. The result of aligning the chronologies in this way is shown in Figure 11.

3.3.2. Independent Verification of Dating

[36] One method of independently verifying the dating model is to compare the chronology with an increment width series from a shell from the same site with a known
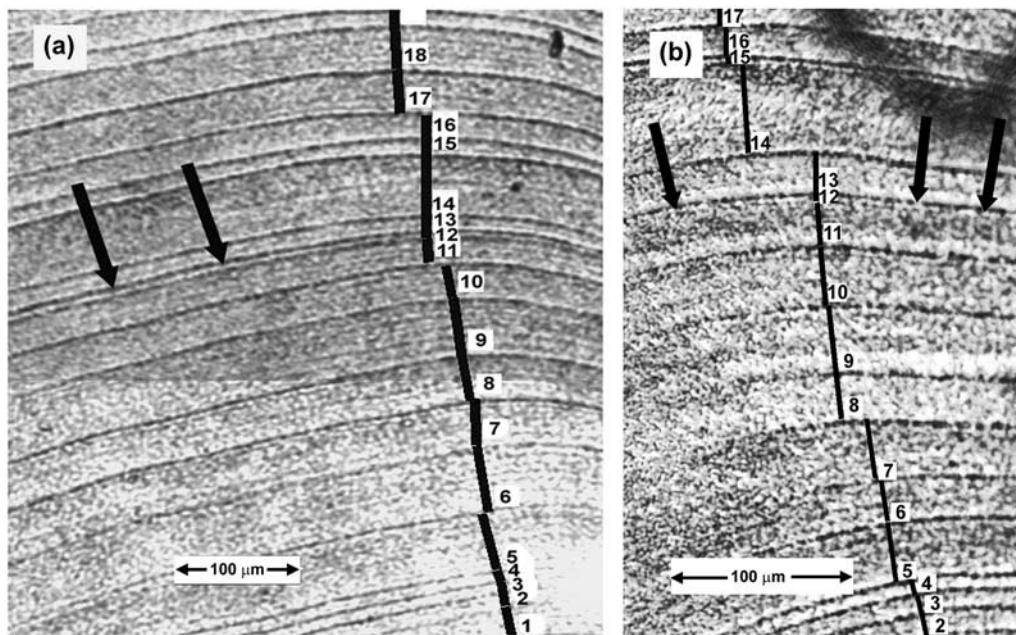

Figure 8. Photomicrographs of acetate peels. (a) Shell 0401423L, showing the "1969" increment indicated by the black arrows at 12. (b) Shell 0401436L, showing that "1969" is missing and has been inserted between 11 and 13.
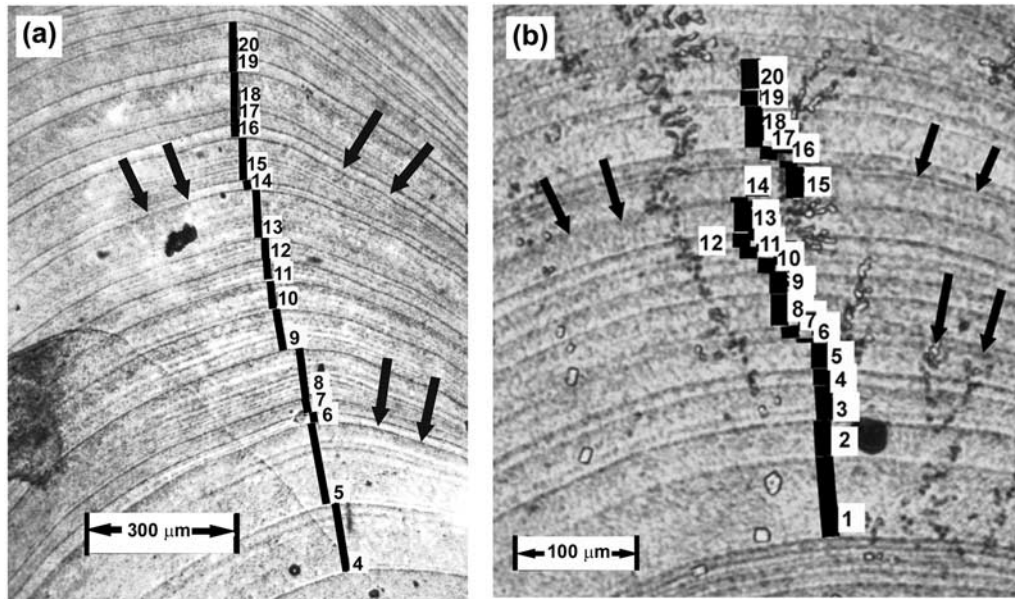
Figure 9. Photomicrographs of acetate peels. (a) Shell 0401423L clearly showing the "1937," "1945," and "1947" increments (arrowed at increments 6, 14, and 16, respectively). (b) Shell 0401409L has "1937" and "1945" missing (shown as inserted increments at 6 and 14), whereas "1947" is present as a thin increment (16). Note the different scales.

date of death close to the beginning of the chronology period. If the SHELLCORR comparison shows a positive correlation which is offset from the presumed date of the chronology, this may indicate one or more dating errors in the chronology. It remains necessary to treat such an apparent link with caution, however, particularly if only a single shell is available for comparison. The strength of the correlation, the number of data points correlated and the number of offsets that might give a meaningful indication are all factors that can reduce the statistical significance of any apparent link. The expression of the common signal can also be reduced because of (1) increased variability associated with the ontogenetic age of the shell and possible enhanced influence of life effects (see section 3.1) and (2) the distance between the collection site of the shell used for verification and the chronology site. Nevertheless, measurements taken from a shell sourced from Zoological Museum, University of Kiel, Germany provide interesting, although ultimately inconclusive, comparisons. This shell (hereafter referred to as BRS; referenced in the work of *Schöne et al.* [2005b, Table 1] as sample ID MOL 8216_05.III.St13-A1R) was recorded as live collected in March 1905 from a position (58°36.5′N, 2°21.3′E) about 135 km to the southeast of sites F and B and about 120 km to the east of site C (see Figure 1). Its lifetime, determined by the number of increments measured in the shell margin, was 40 years. When compared with chronologies from site F (see Figure 12), it appears to correlate weakly through a period of about 15 years at an offset of 4 years, thus providing support for the removal of four doubtful increments from FB. The same offset is apparent in the comparison with the chronology from site C (which is also the geographically closest site to the collection point of BRS).

When compared with the B chronology, however, weak but consistent positive correlations occur at offsets of 0 and 2 years through periods of up to 20 years, supporting the inclusion of all the doubtful increments or alternatively the removal of two of them.

4. Discussion

4.1. Coherence of Individual Series Within Each Chronology

[37] Statistical criteria (GLK, r, t_{BP}, and EPS (Figures 3 and 4)) indicate high coherence between pairs of increment width series. The values (including the minimum values) of each statistic are well above the levels (65% for GLK, 0.36 for r ($p = 0.0001$), 3.5 for t_{BP} and 0.85 for EPS; $n = 110$) required to show high significance. The shells from site A are noticeably the least well correlated of the five sites (for reasons described below), but apart from the period before 1910 when A_{EPS} drops below the threshold value, they are fully acceptable for the construction of a functional chronology. A_{GLK} is not significantly lower than GLK for the other chronologies, probably because of the effect on the mean of one particularly coherent pair of series, but the mean value of r for A is clearly lower than that of the others. t_{BP} is further degraded for A because the most well correlated pair of series (010644L and 0400147L) also has the shortest overlap and A_{EPS} is relatively low throughout the chronology period because the EPS calculation (section 2.5) emphasizes the influence of Rbar, the mean value of r. The four chronologies excluding A appear to be equally internally coherent. The single noticeable difference is that B_{EPS} is slightly lower than C_{EPS}, $F1_{EPS}$ and $F5_{EPS}$, probably because it has a marginally lower value of Rbar.
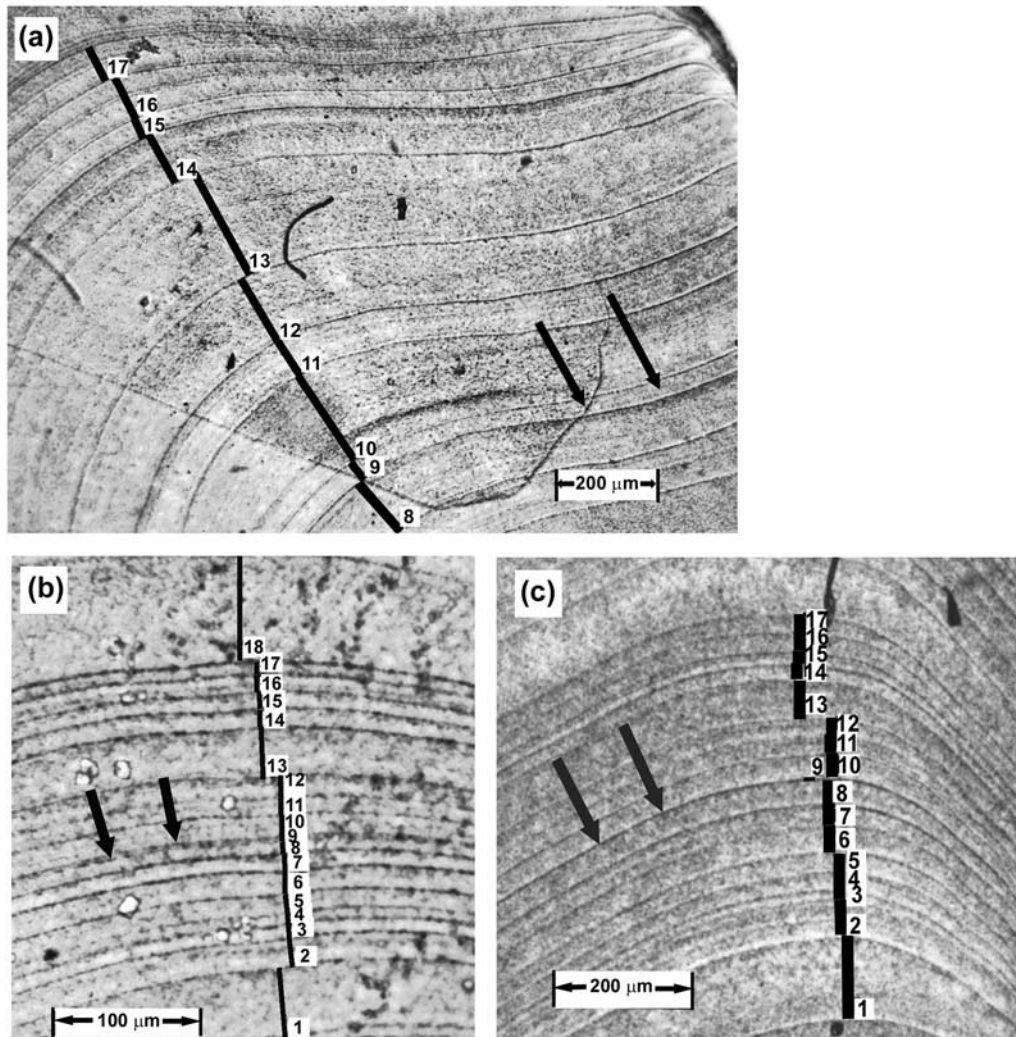
Figure 10. Photomicrographs of acetate peels. (a) Shell 0401423L shows "1923" as a clear increment (9), whereas (b) shell 0401409L shows it as barely visible, and (c) in shell 0401391L it is missing (inserted between 8 and 10).

[38] The chronology construction process was designed to ensure that the strength of expression of the common signal within each chronology could be compared without bias. For this reason, each chronology consisted of five series and the period covered by each series was restricted to the years 1870–1979. However, it was not always possible to identify five series covering the full period. The influence of reduced sample depth on EPS during the period before 1910 has been mentioned earlier (section 3.1) and the following further constraints on the chronologies can be identified which are also likely to affect the expression of the common signal.

4.1.1. Availability of Shells

[39] Where a good supply of shells covering the chronology period is available, the expression of the common signal can be enhanced by selecting those shells whose increment width records show the strongest correlations with each other. For site C, for example, 18 shells were available with

lifetimes greater than 100 years and ^{14}C dates which placed their dates of death after the 1950s bomb pulse. Site A, by contrast, supplied only 5 shells with suitable lifetimes and dates of death. In this case, it was necessary to use all of them in the chronology and there was no scope to select against poor correlations.

4.1.2. Date of Death and Subsequent Degradation

[40] The physical condition of the shells from site A was often degraded when compared with shells from the other sites. Consequently, the peels used to measure the increments were often of poor quality, the identification of growth lines and increments was difficult and the frequency and magnitude of measurement errors was increased. In part, this resulted from the reduced availability of suitable shells from site A, but it may also have been related to the post mortem environment and the length of time between death and collection. All shells used in chronology A died during the period 1965–1981, whereas those used in

Table 2. Assessment of the Visibility of Five Intermittently Occurring Increments in Magnified Peels From the Hinge Plate Region of 17 Shells From Site F

Year	Visible	Faint or Partial	Missing
"1923"	3	6	8
"1937"	9	3	5
"1945"	9	4	4
"1947"	14	2	1
"1969"	2	3	12

chronology C died slightly more recently (1984–1994) and hence may not have been subject to as much deterioration.

4.1.3. Life Effects

[41] The EPS (Figure 4) and the correlations between chronologies (Figure 6) are generally weaker during the earlier years of the chronology period than they are during the middle years (~1900–1960). This may be an artifact of the use of shells which are from roughly the same cohort. During the early part of the period (1870–1890) the shells used in the chronologies are usually juveniles and their increments are wider than those formed in the mature phase of the animals' lifetimes. Although the magnitude and variability of the increments in the juvenile phase are stabilized by power transformation and detrending, the observation that shell growth is the primary objective of energy expenditure at this time of life suggests that the influence of metabolic processes on growth may be enhanced and that of external forcing factors may be diminished. If several shells in the juvenile phase are included in a chronology, the common environmental signal may be partly obscured by statistical noise attributable to metabolic variability.

4.2. Spatial Coherence of the Chronologies

[42] Statistical coherence between chronologies is an indication of the range of the common signal. This is superimposed on the internal coherence of each individual chronology, and it is therefore to be expected that the diminished internal coherence of chronology A will be reflected in relatively weak associations with the other chronologies. Figure 5 shows, for all the statistical criteria, that the coherence between chronologies becomes weaker with distance, and also that the slope of the trend is steeper where chronology A is one of the pair being compared.

[43] The trend to weaker associations is less obvious in the case of GLK. Although there is a significant fall between zero and 40 km, the curve appears almost flat at greater distances, so that the GLK between C and F1/F5 (82 km) is very similar to that between B and F1/F5 (48 km). GLK is a relatively coarse measure of synchrony which degrades the comparison between the two times series to a discrete state model which can take one of three positions (same change, opposite change, and one series does not change). GLKs at distances from 40 km to 80 km are typically between 70% and 75%, whereas for the F chronologies GLK is above 85%. GLK is robust so long as the increment width time series show strong high-frequency variability, but it can decrease if variability is weak or if measurement errors become significant because the increments are very narrow or difficult to discern. The flattening

of the GLK curve at distances greater than 40 km suggests that a significant proportion of the larger year-on-year changes may be robust over very large distances. The correlation coefficient (r) and the Baillie-Pilcher t value (t_{BP}) clearly decrease with distance, although only in the case of the comparisons between A and F1/F5 does the statistical significance become marginal.

4.3. Changes in the Coherence of the Chronologies Through Time

[44] Running correlation coefficients between the pairs of chronologies (Figure 6) showed changes through time in the relative strength of the associations. This can most usefully be approached by splitting the 110-year period into three parts.

[45] 1. Alignment of the chronologies for the period from 1870 to 1900 is constrained because coverage of the years before 1870 is sparse or absent, particularly in the A and F1/F5 chronologies. Without well-established signature years in the period before 1870 to provide an end-member for the dating model, it is difficult to identify without ambiguity a dominant interpretation of the increment patterns in the years immediately following 1870. Consequently, this period is especially vulnerable to unresolved mismatches, such as the offsets that are apparent around 1890 in the matches between A and B and between A and F5. The direction of these offsets indicates that a false increment may have been included in A or that an increment is missing from B or F5. It has not been possible so far to identify an interpretation that resolves the mismatches and at the same time consistently reflects the visible increment patterns.

[46] 2. The interval 1900–1960 is a period of strong and consistent coherence between all five chronologies, and may indicate the optimal spatial coherence that obtains when all the sites are subject to a common hydrographic regime.

[47] 3. After 1960 some of the chronology pairs, which had previously been closely linked, appear to decouple. This is shown most clearly in the relationship between C and F1/F5, whose strong positive correlations terminate in the early 1960s (Figures 6h and 6i). A similar decoupling process probably affects the link between A and F1/F5, although it is more difficult to distinguish the weakening in this case from other periods of lowered correlations involving chronology A. Since C and F1/F5 seem to have become fully decoupled by the mid-1960s, it is noteworthy that the spatially intermediate chronology B retains a positive (and
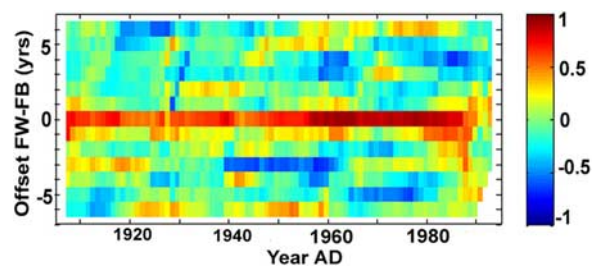

Figure 11. Comparison between FB and FW (as Figure 7) but after the four doubtful increments for "1923," "1937," "1945," and "1969" have been removed from FB.
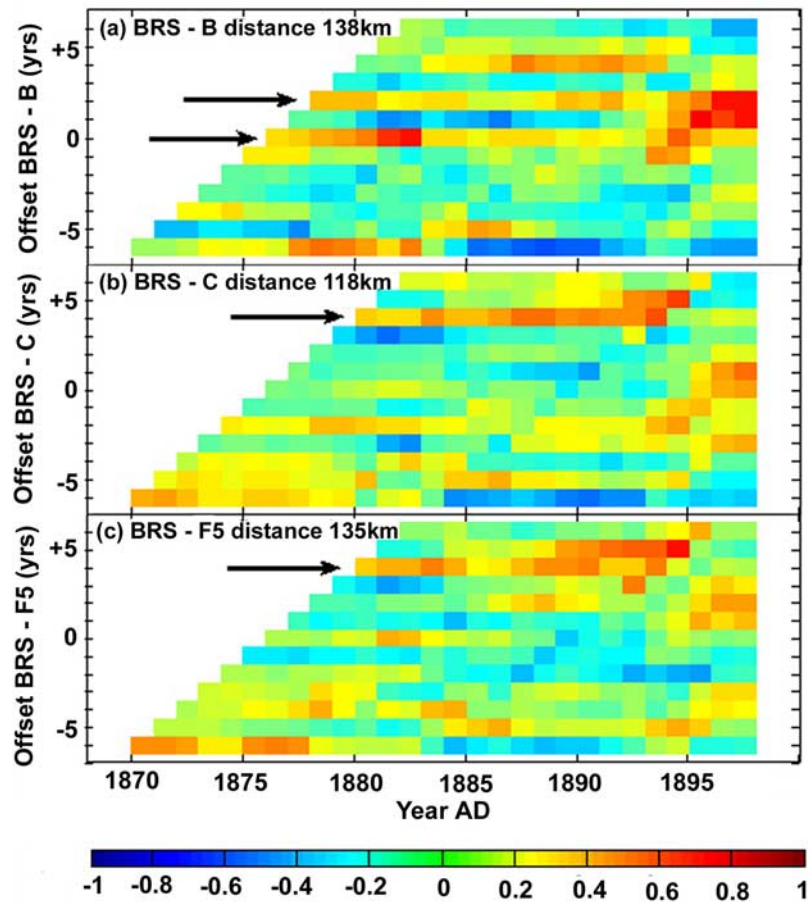
Figure 12. Comparison between shell BRS and chronologies from (a) site B, (b) site C, and (c) site F. Stronger positive correlations mentioned in the text are shown with arrows. Correlation coefficients are shown in a 13-year window at offsets between −6 and +6.

only slightly weakened) correlation both with C and with F1/F5 through to the end of the chronology period (Figure 6e, 6f, and 6g). The decoupling described here is precisely equivalent to that reported by *Witbaard et al.* [1997], whose "North" and "South" chronologies are based on shells from sites identical to those used in this study for chronologies F1/F5 and C respectively. It is explained by *Witbaard et al.* [1997] as a consequence of a change in the position of the northern edge of a topographically steered eddy which led to significantly different benthic food supply regimes at the two sites. The finding that weakened correlations between growth at B and growth at both C and F1/F5 are maintained after the decoupling is consistent with the hypothesis that B is subject to a limited degree to elements of the conditions affecting both other sites and that it is therefore close to the edge of the eddy.

4.4. Comparison Between the FB and FW Chronologies: Identification and Interpretation of Intermittent Increments

[48] The initial misalignment of chronologies FB and FW (Figure 7) demonstrates the potential slippage that may occur between chronologies if different working assumptions are made about the identification of growth incre-

ments. This is a critical issue in sclerochronology, since accuracy of the dating model is an essential prerequisite for the successful construction of absolute chronologies. The use of the increment widths or of geochemical analyses of the shell material for precise high-resolution studies of climatic change would be precluded if the dating model was in any way questionable. The key question is how to interpret narrow intermittently occurring increments of the kind analyzed in section 3.3.1.

[49] The range of circumstances which might result in the appearance of intermittent increments can be usefully divided into three principle categories.

[50] 1. They may be genuine annual increments. If they are not visible, this is because the amount of carbonate secreted during the year was not sufficient to allow two adjacent growth lines to be differentiated.

[51] 2. They may be false annual increments, produced by animals which respond to an environmental cue but which subsequently resume growing (perhaps because the cue was an unseasonal weather event) for a short period and later respond to the appropriate cue. This kind of event might be responsible for the characteristic sequence of a narrow increment followed by a much wider increment (more often observed in shallow water specimens than in shells from

Table 3. Rank Order in Each Chronology of the Standardized Growth Indices of Intermittently Occurring Increments in Shells From Site F[a]

Chronology	"1923"	"1937"	"1945"	"1947"	"1969"
A	26	7	15	29	21
B	23	4	32	1	18
C	50	13	49	4	70
F1	7	1	6	20	4
F5	5	2	12	11	8

[a]Increments are ranked in increasing order of width, so that a low number indicates a narrow increment.

deeper water) that is sometimes known as a "doublet" [*Foster et al.*, 2009].

[52] 3. They may result from a temporary cessation of shell growth after a specific shock event such as storm action, predator attack or fishing disturbance [*Richardson*, 2001]. Apart from predator attack (which would likely be specific to an individual clam), all these scenarios may result in the occurrence of synchronized increments in a subset of the population.

[53] The problem of intermittently occurring increments cannot be resolved simply by examining more shells from the same site. Unless the initial batch of shells examined came from an atypical subset of the population, it is likely that the problematic increments would continue to occur with the same frequency in subsequent batches. A successful approach has to be one that is independent, in time, in space, or in measurement technique, of the initial observations.

4.4.1.   Independence in Time

[54] The existence of significant continuous sequences of well-matched and unambiguous increments is not in dispute (Figure 7). If a shell with a known date of death (established independently of the chronology) prior to the date of the intermittent increments could be matched into the chronology, thus independently establishing the dates of at least one of these unambiguous sequences, then the status of some or all of the subsequent intermittent increments could be deduced. This is equivalent to the dendrochronological technique of using wood of known date from archeological sites to constrain dating models in tree ring chronologies. In the case of *A. islandica* chronologies, the only practical sources of suitable material are museum or private collections of shells with recorded collection dates. Ideally, the shell used for verification should be reasonably long lived (furnishing a continuous time series of at least sixty increments) and it should have been collected from the site used for the chronology being verified. Although no shell has so far been identified which has precisely these characteristics, the ambiguous result obtained using the German museum specimen BRS (see section 3.3.2 and Figure 12) does indicate that for a verification shell to be useful it should correspond quite closely to the ideal. It is likely that the short lifespan of BRS (40 years) and its significant distance from the study site (between 120 km and 135 km), have together weakened any correlation with the chronology to the point where it is indistinguishable from the background. Figure 12 presents three distinct offsets with positive correlations, none of which appears to be significantly stronger than the others. If one of them is correct, it follows

that the other two (which are no less significant statistically) result from random noise.

4.4.2.   Independence in Space

[55] The geographical isolation of existing shell-based chronologies has meant that it has not until now been possible to assess the dating model of a series by comparing it with a neighboring series. This is nevertheless a powerful method of harmonizing the interpretation of intermittent increments, since the chronology standardized growth indices (SGIs) change with respect to one another as the distances between them change. If the intermittent increments are genuine annual increments which are sometimes too small to be measurable, spatial changes are likely to result in the SGIs for these years being slightly wider and less intermittent in at least some of the neighboring chronologies. Conversely, if they are caused by a local disturbance that affects only a subset of the population, it is likely that they would be missing from all of the neighboring chronologies. This hypothesis can be tested by ranking all the increments in each chronology by width and then comparing the positions in the rank order of the SGIs for the doubtful increments analyzed in section 3.3.1. Table 3 shows the position of the SGIs of the doubtful increments among all 110 SGIs (representing the years 1870–1979) after they have been ranked in ascending order of width for each chronology. "1923," "1945" and "1969" are all considerably wider in A, B and C than they are in F1 and F5. "1937" is a narrow increment in all the chronologies but is still narrowest of all in F1 and F5. "1947" appears wider in F1 and F5 than it does in B and C, but it should be noted that this was the least doubtful of the analyzed increments and was missing in only one of the series from the F site (Table 2). The key finding, however, is that none of the increments from the F site that were identified as doubtful are missing from any other chronology (although they may still be missing or partial in some of the individual series). If any were missing from any chronology, this would be evident in some of the SHELLCORR images in Figure 6 as an abrupt jump to +1 or −1 in the offset of strongest correlation. In practice, the strong correlation coefficients at offset zero pass unaffected through the years with doubtful increments, showing that the intervening unambiguous sequences of good correlation are correctly aligned in all the chronologies. This constitutes strong evidence in favor of the acceptance as genuine of narrow increments that are not necessarily visible in all series.

4.4.3.   Independence of Measuring Technique

[56] Intermittently occurring increments, where they are visible, are often not visually distinguishable from adjacent unambiguous increments (see, for example, Figure 10a). If the annual cycles in the shell can be measured independently of direct observation of the increments, the status of the doubtful increments can be confirmed and a more consistent methodological approach to visual increment identification can be adopted. The most widely adopted and reliable geochemical method of reading a seasonal signal in shell material is to measure multiple stable oxygen isotope ratios ($\delta^{18}O$) along a transect between two growth lines. The functional relationship between $\delta^{18}O$ in *A. islandica* and ambient temperature is discussed in detail

elsewhere [*Schöne et al.*, 2005a, 2005b]; it is sufficient here to point out that as the ambient temperature rises $\delta^{18}O$ of the carbonate shell material falls. The sawtooth pattern characteristic of $\delta^{18}O$ analyses of *A. islandica* shell [*Schöne et al.*, 2005a; *Weidman et al.*, 1994; *Witbaard et al.*, 1994] shows a trend of increasing temperature (falling $\delta^{18}O$) through each increment and indicates that the growth line forms at or shortly after the point of maximum ambient temperature (minimum $\delta^{18}O$).

[57] In principle, it should be possible to measure $\delta^{18}O$ through an intermittently occurring increment and two adjacent increments. If the seasonal trend to lower $\delta^{18}O$ passes through one of the growth lines without deviation, this can be seen as evidence that the doubtful increment is not a genuine annual increment. $\delta^{18}O$ measurements through so-called doublets (section 4.4) reported by *Foster* [2007] are consistent with this hypothesis but cannot be regarded as conclusive because only two data points could be sampled in the narrow phase of the doublet. The shells used by *Foster* [2007] were collected from a water depth of only 6m, and this observation may be a further indication of the likelihood that the increments in *A. islandica* from shallow waters are often subannual and are not synchronized [*Epplé et al.*, 2006; *Turekian et al.*, 1982]. In practice, the ability to obtain a meaningful seasonal signal from $\delta^{18}O$ measurements in a narrow increment is constrained by the spatial resolution of the sampling technique. The minimum increment width that would be required to obtain four samples with a sampling resolution of around $20\,\mu m$ [*Schöne et al.*, 2005a] is $70\,\mu m$. Assuming the samples are taken from the shell margin, this constraint restricts the range within which narrow increments can be sampled to the first $\sim$40 years of life. In order to examine the increment for any particular year, it would be necessary first to identify a shell which included that year in its first 40 years and then to correctly identify the target increment. This is by no means unfeasible, but it does indicate why no isotopic studies of *A. islandica* have yet explicitly addressed this issue.

5. Conclusions

[58] The spatial coherence of synchronous growth among populations of *A. islandica* in the northern North Sea is high. This coherence extends at least as far as 80 km and probably operates at greater distances. It appears to be sensitive to hydrographic changes and there is therefore potential to use *A. islandica* populations in this area as a proxy for changes in the inflow to the North Sea from the North Atlantic and hence as a proxy for changes in the strength of the North Atlantic current [*Witbaard et al.*, 1997, 2003]. The *A. islandica* chronology network has considerable potential to be extended in space and in time. Populations of live animals and sources of subfossil shell are known from several sites in the Fladen Ground to the south of those described here [*Scourse*, 2006, p. 95], and from elsewhere in the North Sea [*Witbaard and Bergman*, 2003]. A 300-year floating chronology exists for site A which can be constrained by ^{14}C dating to the period between AD 1000 and AD 1400 [*Scourse et al.*, 2006] and the ^{14}C dates of subfossil shells collected from the northern North Sea indicate that a long chronology of at least 1000 years is feasible.

[59] Comparison between neighboring chronologies strongly indicates that narrow intermittently occurring increments can generally be interpreted as true annual growth increments. If this conclusion is confirmed by geochemical studies and by further research into spatial coherence the likelihood of systematic slippage impacting the *A. islandica* chronologies will be significantly reduced and confidence in the integrity of the absolute dating models will be enhanced.

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C. L. Bryant, NERC Radiocarbon Laboratory, Scottish Enterprise Technology Park, Rankine Avenue, East Kilbride G75 0QF, UK.

P. G. Butler, N. M. Fraser, C. A. Richardson, J. D. Scourse, and A. D. Wanamaker Jr., School of Ocean Sciences, College of Natural Sciences, Bangor University, Menai Bridge LL59 5AB, UK. (osp03e@bangor.ac.uk)

I. Harris, Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK.

I. Robertson, Department of Geography, School of the Environment and Society, Swansea University, Swansea SA2 8PP, UK.

B. R. Schöne, Department of Applied and Analytical Paleontology, Institute of Geosciences, Johannes Gutenberg University of Mainz, Johann-Joachim-Becherweg 21, D-55128 Mainz, Germany.

R. Witbaard, Department of Marine Ecology, Royal Netherlands Institute for Sea Research, P.O. Box 59, NL-1790 AB Den Burg, Texel, Netherlands.