Absolute chronologies from the ocean: Records from the longest-lived, non-colonial animals on Earth

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Although there is an extensive network of annually dated, terrestrial-based proxies in the northern hemisphere for the last millennium (e.g., NRC, 2006), such records are scarce in the marine realm. Most existing annually resolved, marine-based proxy records (corals) are biased to the tropical oceans. In part, research in the mid- to high-latitude oceans has been hindered by a lack of suitable high-resolution marine archives for sclerochronological studies. Sclerochronology is the broad study concerning the accretionary hard tissues of organisms (e.g., mollusks, corals, fish) and can be regarded as the aquatic counterpart of dendrochronology. Sclerochronological techniques are used to develop a master chronostratigraphy within biogenic carbonates, which is then used as a template for growth and geochemical analysis.

The long-lived bivalve mollusk *Arctica islandica* (Linnaeus, 1767), common in the shelf seas of the temperate to sub-polar North Atlantic, has enormous potential as a high-resolution marine archive. This stationary benthic clam is highly suitable for environmental and climate studies because (1) it is extremely long-lived (up to 3-4 centuries; Schöne et al., 2005; Wanamaker et al., 2008a), (2) it produces annual increments in its shell (Jones, 1980; Fig. 1), (3) regional increment series can be cross-matched, demonstrating a common response to environmental forcing(s) (Schöne et al., 2003; Fig. 2), (4) fossil shells can be cross-matched and floating shell chronologies can be constructed after radiocarbon dating (Scourse et al., 2006), (5) live-caught shells can be cross-dated with fossil shells to assemble very long, absolutely dated growth records (Marchitto et al., 2000), (6) master shell chronologies can be created that are as statistically robust as tree ring chronologies (Witbaard et al., 1997; Helama et al., 2007), (7) *Arctica islandica* is widely distributed in the mid- to high-latitudes of the North Atlantic throughout the Holocene (see Scourse et al., 2006), and (8) the geochemical signature (^{14}C, $\delta^{18}O$, $\delta^{13}C$) from the shell material and master shell-growth chronologies can be used to reconstruct ocean circulation, hydrographic changes, and ecosystem dynamics (Weidman and Jones, 1993; Weidman et al., 1994; Witbaard et al., 2003; Schöne et al., 2005; Wanamaker et al., 2008b). The generation of annually resolved marine proxy data from the extra-tropical Atlantic Ocean, using *A. islandica* and other suitable archives (e.g., Halfar et al., 2008) to document and interpret environmental change, will be a major research goal for the next decade of marine paleoclimate research.

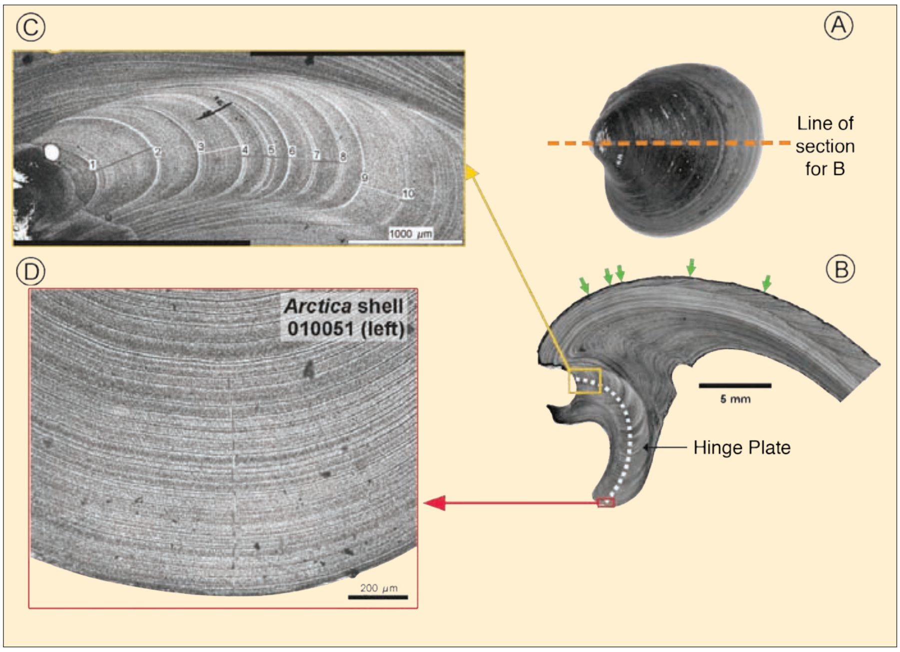

Figure 1: Idealized preparation of an Arctica islandica *shell for sclerochronological studies (from Scourse et al., 2006).* ***A****) External valve face, showing line of section through the left valve used to generate acetate peel replicas;* ***B****) Acetate peel replica cross-section of valve showing 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;* ***D****) Narrow senescent late bands from the outer part of the hinge plate axis.*

Some *A. islandica* research highlights

Weidman and Jones (1993) first showed the potential for using the radiocarbon content from the annually banded shells of *A. islandica* to monitor ocean circulation in the northwestern Atlantic (Georges Bank). Interestingly, the oceanic response to atmospheric-bomb testing during the

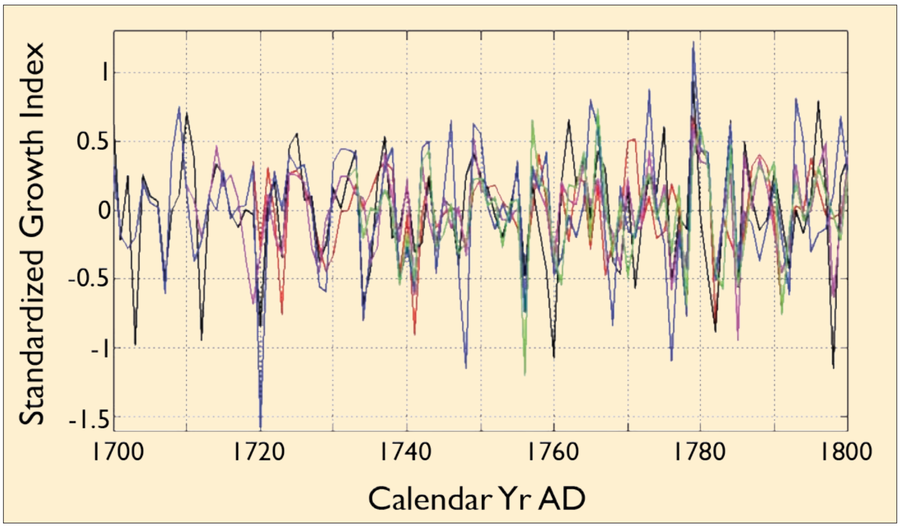

Figure 2: Incremental growth series measured from five dead-collected A. islandica *shells from the Irish Sea (off the Isle of Man) showing a high degree of synchronicity. Data are from P.G. Butler (unpublished). Each shell growth record was normalized with a natural logarithmic function, then detrended with a 15-year spline to remove the ontogenetic growth trend.*

1950s on Georges Bank was attenuated compared to the tropical Atlantic. This result highlighted important differences in ocean mixing processes between the low- and mid-latitudes, and it likely indicated that there was a deepwater source for the waters of Georges Bank. Further, it was illustrated that the oxygen isotopes from the shell material of *A. islandica* were precipitated in isotopic equilibrium with the ambient seawater ($\delta^{18}O_{water}$) (Weidman et al., 1994). Therefore, sub-annual to annual seawater temperature records could be constructed if the $\delta^{18}O_{water}$, which is related to salinity, could be constrained. It was later shown that absolutely dated master *A. islandica* shell chronologies could be accurately constructed from live-caught and fossil material (Marchitto et al., 2000). Recently, it was demonstrated that fossil *A. islandica* shells could be successfully cross-matched using initial 'range finding' radiocarbon measurements and a rigorous comparison among shell growth series (Scourse et al., 2006). In the North Sea, shell growth records from *A. islandica* were used to infer changes in zooplankton cycles and productivity, which seemed to be in part related to the North Atlantic Oscillation (NAO) (Witbaard et al., 2003). Schöne et al. (2003) showed a remarkable positive relationship between the winter NAO index and *A. islandica* shell growth series from the central North Sea and the Norwegian shelf, and suggested that the NAO was impacting shell growth via its influence on food supply.

Recently, with ultra-high-resolution sampling of an *A. islandica* shell, it was demonstrated that there is no ontogenetic trend in oxygen or carbon isotopes (Schöne et al., 2005). This result is important for reconstructing past ocean environments because it means that geochemical records from both young and old shell portions can be used to infer past conditions. In addition, it was found that *A. islandica* off Iceland continue to deposit shell material during the winter months, indicating that there is no substantial 'shut-down' period (Schöne et al., 2005). This result was later corroborated in the Gulf of Maine (Wanamaker et al., 2008b). The data illustrated in Figure 3 shows that *A. islandica* is comparable to corals, providing ultra-high-resolution proxy records for centuries at a time.

Recently, we counted 405 annual bands in a sectioned *A. islandica* shell from the north Icelandic shelf, and radiocarbon analysis from the first annual shell layer (ontogenetic age 0-1) confirmed its sclerochronological age (Wanamaker et al., 2008a). We then calculated the reservoir age of the waters north of Iceland for ca.

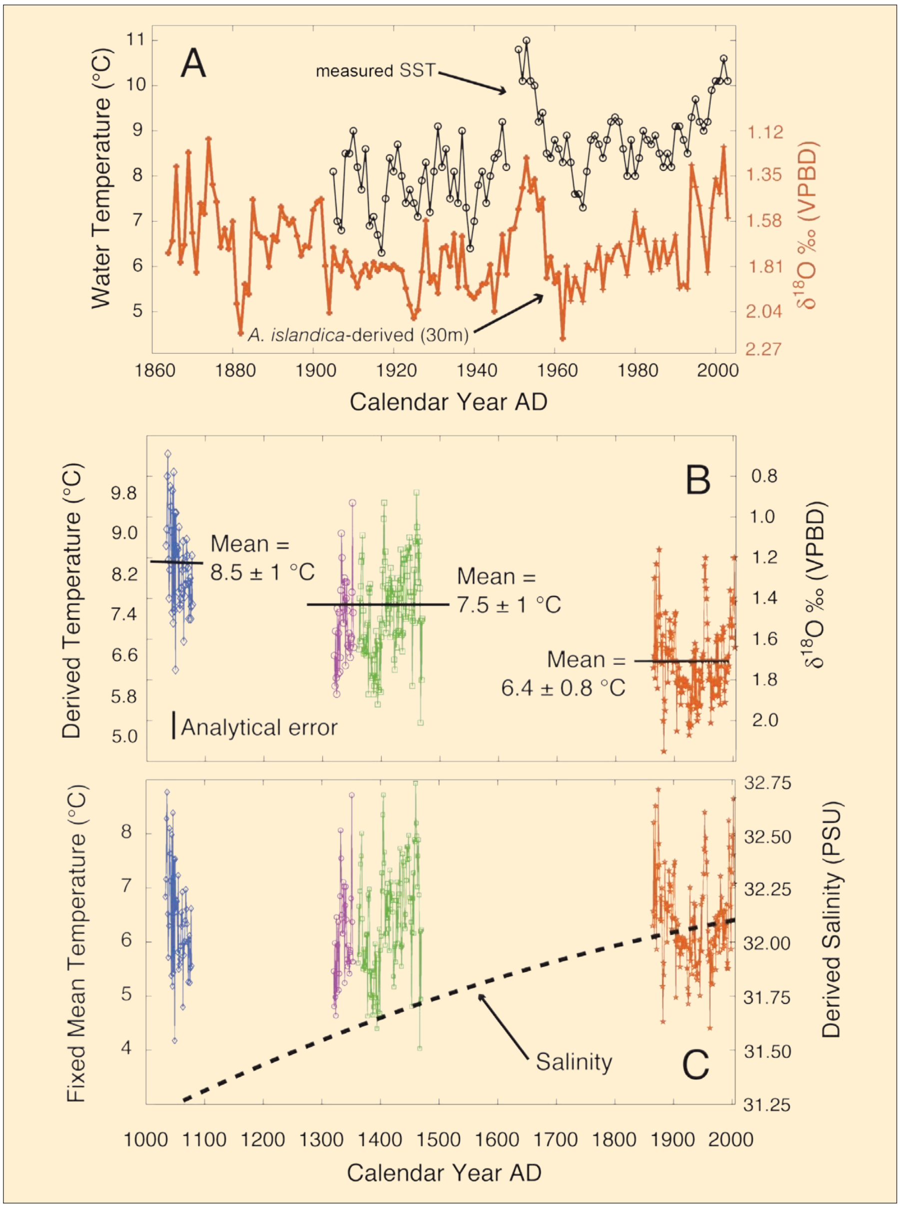

Figure 3: Oxygen isotope record ($\delta^{18}O$) from A. islandica *shells from the Gulf of Maine (modified from Wanamaker et al., 2008b);* ***A****) Modern relationship between a local sea surface temperature (SST) instrumental record and the shell-derived water temperature at 30 m water depth. Nearby salinity values from 1928-2003 were used to constrain $\delta^{18}O_{water}$ values, based on an established salinity/ $\delta^{18}O_{water}$ mixing line;* ***B****) Late Holocene shell-derived water temperatures (based on mean 50 m salinity values prior to 1928) and $\delta^{18}O$ record (indicates a cooling trend over the last millennium);* ***C****) Late Holocene shell-derived water salinity. Dotted line represents possible salinity increase in the Gulf of Maine if long-term mean annual seawater temperatures remained constant. The data in both (B) and (C) estimate maximum end-member conditions for the Gulf of Maine (see Wanamaker et al., 2008b for details).*

AD 1600, which was found to be 637 ± 35 ^{14}C years. This reservoir age compares rather well with tephra-based ages from sediment cores from the same location, which are about 600 ^{14}C years at AD 1650 (e.g., Eiríksson et al., 2004). The >400 year *A. islandica* is considered to be the oldest mollusk yet discovered and perhaps the longest-lived non-colonial animal. We have begun to build a 1000-year master shell chronology from the north Icelandic shelf to reconstruct paleoceanographic changes in a region that is very sensitive to climate change. Preliminary results indicate that shell growth from the north Icelandic shelf is highly synchronous among samples from this region, and approx. 50% of the interannual growth variation is related to seawater temperatures during the summer (Wanamaker et al., 2008a).

Future applications

Shell data from *A. islandica* can be used to reconstruct meridional overturning circulation changes in key regions in the North Atlantic. Radiocarbon analyses from *A. islandica* shells can provide a continuous calibration of the marine reservoir age with an absolutely dated chronology (e.g., Wanamaker et al., 2008a). Furthermore, data from master shell chronologies can help characterize rates and/or the type of change (step-like, monotonic, complex) over key climate periods during the Holocene (e.g., 8.2 kyr event, Medieval Warm Period/Little Ice Age transition, and 20th century warming) in key oceanographic settings. Ultra-high-resolution geochemical data can provide seasonal information (amplitude and variability) on water temperature changes and seasonal stratification dynamics for the shallow shelf seas in the North Atlantic. Recent advances in geochemical techniques, including the "carbonate clumped isotope" method (Ghosh et al., 2006; Came et al., 2007), provide an excellent opportunity to reconstruct past ocean temperatures independent of $\delta^{18}O_{water}$ or salinity using *A. islandica* and other suitable archives. Although *A. islandica* is restricted to the North Atlantic, other long-lived bivalves with annual banding, such as the geoduck clam (*Panopea abrupta*) from the Pacific, can also serve as reliable climate proxies (e.g., Strom et al., 2004), extending the geographical range in which ocean climate can be reconstructed using the methods described here.

Summary

A. islandica is a remarkable, yet underutilized, marine archive. Geochemical and master shell-growth records have the potential to greatly improve our understanding of key climate events/transitions, as well as ecosystem changes in the North Atlantic throughout much of the Holocene. Its great longevity, its fidelity as a proxy record, and its abundance and wide geographical distribution make *A. islandica* a key proxy archive for the North Atlantic region.

Acknowledgements

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Note

Isotope data for Figure 3 is available from the NOAA paleoclimate database www.ncdc.noaa.gov/paleo/data.html

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On the abyssal circulation in the Atlantic basin at the Last Glacial Maximum

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Our understanding of oceanic variability on timescales longer than the time span of direct oceanographic measurements (about a century for most common measurements) relies on our capability to interpret the marine sediment record. Sediment observations have reached the point where hypotheses regarding oceanic conditions during specific time intervals of the geological past can be tested. An interval of preeminent interest is the Last Glacial Maximum (LGM, ca. 20 kyr BP), when large ice sheets occupied North America and northern Europe, and global sea level was reduced by more than 100 m. Much effort has been devoted to estimating oceanic conditions during the LGM, in particular in the Atlantic basin. Hypotheses regarding the ocean circulation during the LGM are particularly relevant, given the postulated role of ocean circulation in climate change. Here we report on a test of the null hypothesis that observations from glacial sediments in the Atlantic basin are consistent with the modern circulation.

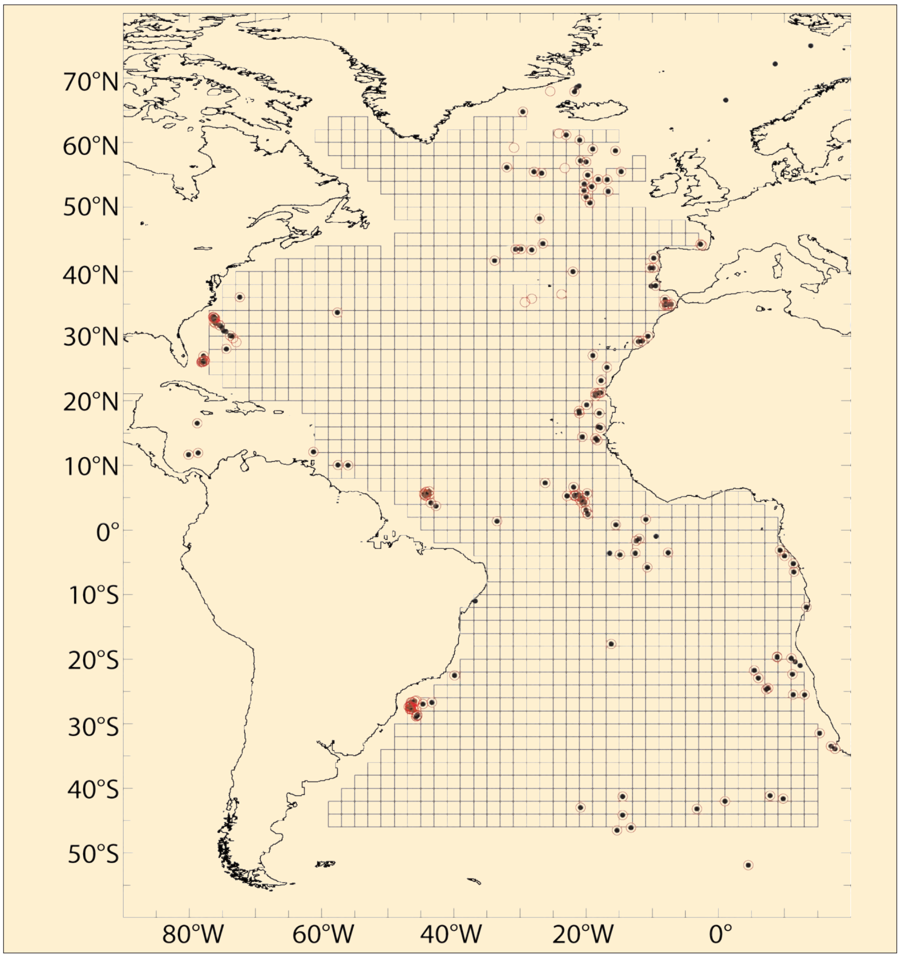

Figure 1: Location of the sediment cores considered in the compilation of benthic foraminiferal data for the Holocene (black dots; 198 measurements; defined as 0-3 kyr BP) and LGM (open red circles; ^{18}O measurements; 18-21 kyr BP). Compilation includes data from both earlier syntheses and other sources. The benthic $\delta^{18}O$ and $\delta^{13}C$ measurements were conducted exclusively on the benthic taxa Cibicidoides *and* Planulina. *Both post-glacial and glacial values are available at most core locations. Locations span the depth range 280–5105 m, with 50% (80%) of the cores from depths shallower than 2500 m (3750 m). Figure modified from Marchal and Curry, 2008.*

A conventional view

Among the most common measurements performed on glacial sediments are two isotopic ratios of calcite shells of benthic foraminifera (bottom-dwelling organisms): the oxygen isotopic ratio $^{18}r = {}^{18}O/{}^{16}O$ and the carbon isotopic ratio $^{13}r = {}^{13}C/{}^{12}C$. Both ratios are usually expressed as a relative