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Comparative sclerochronology of modern and mid-Pliocene (c. 3.5 Ma) *Aequipecten opercularis* (Mollusca, Bivalvia): an insight into past and future climate change in the north-east Atlantic region

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ABSTRACT

Records of environment contained within the accretionarily deposited tissues of fossil organisms afford a means of detailed reconstruction of past climates and hence of rigorous testing of numerical climate models. We identify the environmental factors controlling oxygen and carbon stable-isotopic composition, and microgrowth-increment size, in the shell of modern examples of the Queen Scallop, *Aequipecten opercularis*. This understanding is then applied in interpretation of data from mid-Pliocene *A. opercularis* from eastern England. On the basis of oxygen-isotope evidence we conclude that winter minimum seafloor temperature was similar to present values (typically 6–7 °C) in the adjacent southern North Sea and that summer maximum seafloor temperature was a few degrees lower than present values (typically 16–17 °C). This contrasts with evidence from other proxies that winter and summer temperatures were higher than present. The pattern of seasonal variation in microgrowth-increment size suggests the existence of intense thermal stratification in summer. We therefore conclude that summer surface temperatures were much higher (maxima well over 20 °C) than those recorded isotopically on the seafloor and that the annual range of surface temperature (probably over 14 °C) was greater than now at the times in the mid-Pliocene when the investigated *A. opercularis* were alive. Taken in conjunction with other proxy evidence of warmer winters as well as summers, the data point to substantial fluctuation (up to 10 °C) in winter minimum temperatures during the mid-Pliocene in the north-east Atlantic region. This fluctuation may be attributable to variation in the strength of the Gulf Stream/North Atlantic Drift. Since the Pliocene has been widely used as a test-bed for numerical models of a greenhouse Earth, the results have implications for prediction of future climate in the north-east Atlantic region under the influence of anthropogenic global warming.

1. Introduction

Sclerochronology (Buddemeier and Maragos, 1974) is the study of time-series data contained within the accretionarily deposited mineral tissues of plants (e.g. the skeletal materials of certain multicellular algae) and animals (e.g. the shells of many invertebrates). As in the longer-established sister-field of dendrochronology (involving records in organic tissue: wood), the size of increments is an important datum. However, to a much greater extent than in dendrochronology, geochemical time-series (e.g. of stable-isotopic composition or trace-element concentration) are used in sclerochronology, a reflection of the relative immunity of mineral materials from post-mortem chemical alteration. The time-series data facilitate both measurement of elapsed time and identification of environmental changes during the ontogeny/astogeny of the individual/colony concerned. Dependent on the taxon involved and the techniques used, both the chronological precision and the range of environmental parameters documented may be much greater than from dendrochronological data (e.g. Richardson, 2001; Schöne et al., 2002; Schöne and Surge, 2005; Hallmann et al. 2009).

There have been numerous studies of marine environmental conditions involving time-series of growth-increment size and stable-isotope ratios ($^{18}O/^{16}O$, $^{13}C/^{12}C$) from bivalve molluscs (e.g. Richardson, 2001; Schöne and Surge, 2005). Here we review and substantially supplement such data for modern examples of the Queen Scallop, *Aequipecten opercularis* (Fig. 1), discussing what environmental variables may be reflected therein. We then undertake a similar exercise

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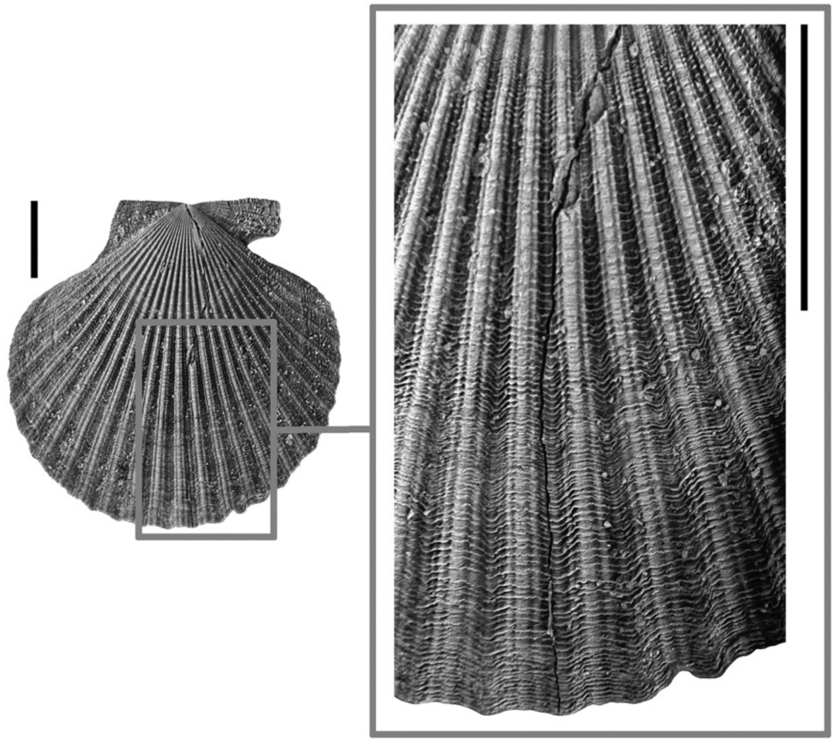

Fig. 1. Right valve of Pliocene *Aequipecten opercularis* (UD 52795) with enlargement showing microgrowth increments of varying size. Scale bar = 10 mm. Growth-increment and isotopic data from this specimen are shown in Fig. 8 and Tables 3 and 4.

for representatives from the mid-Pliocene Coralline Crag Formation of Suffolk, eastern England, a deposit which accumulated under greenhouse conditions shortly before the onset of major northern-hemisphere glaciation. On the basis of the understanding obtained from study of modern *A. opercularis*, and of a test of the Coralline Crag results employing the bivalve *Arctica islandica*, we interpret aspects of the local mid-Pliocene marine environment and subsequently relate these findings to regional and global circumstances. We conclude that in the greenhouse world of the mid-Pliocene there was substantial variation in oceanic heat supply to the north-east Atlantic region. This may give an indication of the future behaviour of the Gulf Stream/North Atlantic Drift in response to global warming.

2. Methods

2.1. Stable isotopes

Hickson et al. (1999, 2000) and Johnson et al. (2000) describe methods used in earlier stable-isotope work on *A. opercularis*. They extracted samples at *c.* 1 mm intervals through shell ontogeny, omitting the first *c.* 10 mm of growth (representative of a few months) because of the difficulty of obtaining sufficiently large, temporally well-resolved samples. For the first 1–2 years of (rapid) growth this sampling protocol achieves at least a monthly temporal resolution, sufficient to characterise seasonal fluctuations in isotopic composition. The supplementary data reported here (seven further profiles from Pliocene shells, one from a modern shell and a single near-margin value from another modern shell) were obtained following essentially the same procedures but with analysis conducted partly at the NERC Isotope Geosciences Laboratory (NIGL), Keyworth, UK (VG Isocarb + Optima system), and partly at the Institute of Geosciences (IGF), University of Frankfurt, Germany (Finnigan MAT 253 continuous-flow mass spectrometer equipped with a GasBench II). The relevant laboratory is indicated in the text. $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios are reported as $\delta^{18}O_{shell}$ and $\delta^{13}C_{shell}$ values versus VPDB by comparison with within-run laboratory standards calibrated against NBS-19 and NBS-18, with a precision (1 SD) typically <0.1‰ for both $\delta^{18}O$ and $\delta^{13}C$. In conformity with earlier published work on *A. opercularis* calcite, estimated temperatures from $\delta^{18}O$ values were calculated using the equation of O'Neil et al. (1969), with 0.26‰ subtracted from the water value ($\delta^{18}O_{water}$; measured versus VSMOW) to compare with VPDB (Coplen et al., 1983).

The *Ar. islandica* specimen from the Coralline Crag Formation used to test the results from *A. opercularis* was sectioned and sampled across the third annual increment by means of a series of immediately adjacent 300 µm-diameter boreholes equidistant from the outer surface. Being representative of the early, relatively rapid phase of growth (Schöne et al. 2005), the third annual increment offered the prospect of high temporal resolution in sampling. Estimated temperatures for the aragonite mineralogy were calculated using the equation of Grossmann and Ku (1986), modified so that water values relate to VPDB rather than VSMOW (Schöne et al., 2005).

2.2. Growth increments

Although we did record the positions of growth-breaks ('growth-rings') marking the boundaries of major increments, our study of *A. opercularis* focused on microgrowth increments on the outer shell surface (Fig. 1). In contrast to previous work employing a microscope fitted with an eyepiece graticule (Johnson et al., 2000), increments were measured on digital images using Panopea© (2004, Peinl and Schöne) software, the shells having been coated before photography with a sublimate of NH_4Cl to improve the clarity of increments. *A. opercularis* valves are of low convexity so measurement of 2D-images of the surface introduces only a trivial error. Some shells (those analysed at NIGL) were isotopically sampled before growth-increment analysis. Of these, some could no longer be measured, while others had to be measured anterior or posterior of the sampling grooves and a correction factor (the ratio of shell height measured along the midline to that measured along the relevant anterior or