Sea ice extent and seasonality for the Early Pliocene northern Weddell Sea

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Abstract

Growth increment analysis coupled with stable isotopic data ($\delta^{18}O/\delta^{13}C$) from Early Pliocene (ca 4.7 Ma) *Austrochlamys anderssoni* from shallow marine sediments of the Cockburn Island Formation, northern Antarctic Peninsula, suggest these bivalves grew through much of the year, even during the coldest parts of winter recorded in the shells. The high frequency fluctuation in growth increment width of *A. anderssoni* appears to reflect periodic, but year-round, agitation of the water column enhancing benthic food supply from organic detritus. This suggests that *Austrochlamys* favoured waters that were largely sea ice free. Our data support interpretation of the Cockburn Island Formation as an interglacial marine deposit and the previous hypothesis that *Austrochlamys* retreated from the Antarctic as sea ice extent expanded, this transition occurring during climate cooling in the Late Pliocene. Our data question climate models that show extensive sea ice in the Weddell Sea during the Early Pliocene.

Keywords: Pliocene, Antarctic, bivalves, seasonality, sea ice, climate

1. Introduction

The Pliocene Epoch (5.3 to 2.6 Ma) spans a time when the Earth experienced a transition from relatively warm conditions to a cooling climate that heralded the high magnitude glacial-interglacial oscillations of the Pleistocene Epoch (Haywood et al., 2009). The warm interglacial climates of the Pliocene may be plausible comparative scenarios for interpreting the path of future climate warming during the 21st century (Jansen et al., 2007; Haywood et al., 2009). Whilst overall global climate may have been 2-3°C warmer during the 'mid Piacenzian warm interval' (= 'mid Pliocene warm period' of earlier papers), climate at high latitudes is modelled to have been much warmer than today (Haywood et al., 2007 and references therein). Given the significance of a warming 21st century global climate and its influence on high latitude sea surface temperatures and sea ice extent, it is important to develop proxies that can ground-truth models of high latitude regions during the Pliocene (e.g. Dowsett, 2007, fig. 6).

Bivalves preserve a signal of marine seasonality (e.g. water temperature, upwelling, food supply) in their carbonate geochemistry and skeletal morphology (e.g. Jones and Quitmyer, 1996; A. Johnson et al., 2000, 2009; Schöne et al., 2003, 2005). These signals have been used to provide climate information across a range of palaeolatitudes (e.g. Williams et al., 2009a). Antarctic Peninsula Neogene fossil bivalves have received detailed taxonomic and environmental appraisal (e.g. Jonkers et al., 2002; Jonkers, 2003) but they have not been used to assemble a record of seasonality. Nevertheless, Berkman et al. (2004) have presented a cogent argument, based on morphological and sedimentological analyses, which suggests that the retreat of *Chlamys*-like bivalves from the Antarctic resulted from increasing sea ice cover during the climate cooling of the Late Pliocene.

The pectinid bivalve *Austrochlamys anderssoni* occurs commonly in rocks of Late Miocene through Pliocene age on the northern Antarctic Peninsula. *Austrochlamys anderssoni* is ideal for investigation of palaeoseasonality as specimens are large, often reaching greater than 10 cm from

umbo to margin in adults, and record a number of seasons of growth. In addition, the width of individual growth increments in *A. anderssoni* is easy to measure (mm-scale), and they are correspondingly easy to sample for geochemical analysis. Here we analyze ontogenetic patterns in *A. anderssoni* to test for the extent of sea ice in the northern Weddell Sea during a warm interval of the Early Pliocene. We test two possible marine scenarios: 1), that there was extensive winter sea ice with no planktonic food-supply, no re-suspension of detrital food and therefore limited or no bivalve growth, an environment suggested by some climate models (see Fig. 1); and 2), no winter sea ice with bivalve growth continuing via a supply of periodically re-suspended organic detritus via water column agitation. We use stable oxygen and carbon isotopes to define seasonal intervals during the growth of *A. anderssoni* and to estimate seasonal temperature variation: we then use growth increment data as a proxy to interpret benthic food supply and sea ice extent.

2. Geological setting

The James Ross Island Volcanic Group (JRIVG) dominates the outcrop geology of James Ross Island, Vega Island and several small islands including Cockburn Island, in the northern Weddell Sea, east of the Antarctic Peninsula (Fig. 2). The volcanic rocks unconformably overlie relatively unconsolidated Cretaceous marine deposits. About 10 million years of late Neogene and Quaternary history is recorded in the JRIVG (Smellie et al., 2006a, b, 2007, 2008, 2009; Hambrey et al., 2008). Sedimentary rocks in the JRIVG are dominated by diamictite conglomerate and minor sandstone (Smellie et al., 2006a; Hambrey et al., 2008; Nelson et al., 2009). Two sedimentary formations have been defined, the interglacial marine Cockburn Island Formation (Jonkers, 1998a, b) and the glacial Hobbs Glacier Formation (Pirrie et al., 1997). Fossils have been recovered from both of these formations, and in addition rare asterozoan trace fossils are preserved in marine-deposited volcanic tuffs (Williams et al., 2006; Nelson et al., 2008). The JRIVG represents an important and largely unexploited archive of late Neogene fossil and geochemical data for reconstructing past climate and seasonal regimes at high southern latitude.

The richest Neogene fossil assemblages in the JRIVG are those of the interglacial marine Cockburn Island Formation, which contains abundant large molluscs, especially *Austrochlamys* (‘*Zygochlamys*’ of Jonkers et al., 2002; see Jonkers, 2003 for a detailed taxonomic appraisal). The glacimarine deposits of the Hobbs Glacier Formation contain similar macrofossil assemblages, are dominated by molluscs (including *Austrochlamys*), but also contain older material reworked from the Cretaceous (Smellie et al., 2006a). Collectively these fossils occur in strata of Late Miocene (ca 6 Ma) through to Pleistocene age (ca 2 Ma). Detailed analysis of the JRIVG has identified three intervals of relative warmth in the northern Peninsula region, when volcanic rocks were erupted into a marine environment (Smellie et al., 2006a, fig. 6). Radiometric ($^{40}Ar/^{39}Ar$) dates from the volcanic rocks, together with $^{87}Sr/^{86}Sr$ chronology from the molluscs in the intervening glacimarine and interglacial marine rocks have produced a well-resolved stratigraphy which constrains the warm intervals to 6.5 to 5.9, 5.03 to 4.22, and ca 0.88 Ma. The *Austrochlamys* material we study here, from the second of these warm intervals, is dated at 4.66 +0.17/-0.24 Ma by McArthur et al. (2006).

3. Provenance of bivalve material on Cockburn Island

The *Austrochlamys* bivalve material is sourced from three localities on the east side of Cockburn Island referred to in BAS archives as DJ.851, DJ.852 and DJ.853 (Fig. 2). This material was collected by H.A. Jonkers in 1996 though the island had been visited on several occasions dating back to 1906 (Jonkers, 1998a). The Cockburn Island Formation forms small outcrops at a number of localities on the island and Jonkers recognised a western ‘proximal’ or ‘littoral’ facies and an eastern ‘distal’ facies. Based on the gradient atop the island he estimated the latter, bivalve-bearing facies to represent original water depths no greater than 100 m. Fossils associated with the bivalves include echinoids, gastropods, brachiopods, serpulids and rare possible penguin bones. The precise stratigraphical relationships of the bivalve material from the three localities documented here is difficult to discern, but they are clearly from the same substratum.

4. *Austrochlamys* as a palaeoenvironmental index of Antarctic shelf waters in the late Neogene

Austrochlamys is an epibenthic pectinid bivalve genus comprising six species whose distribution is restricted to the Antarctic and sub-Antarctic region, with one extant species known from South America (Jonkers, 2003; Quilty et al., 2004). The earliest *Austrochlamys* occur in Oligocene deposits of King George Island (for a summary of fossil occurrences see Berkman et al., 2004). Sub-fossil material is also known from as far north as southern New Zealand (Auckland Islands, Dijkstra and Marshall, 2008). Fossils of *Austrochlamys* are prolific and widespread in strata of Late Miocene through Pliocene age of the Hobbs Glacier and Cockburn Island formations and often are very well preserved (Fig. 3), with specimens articulated even when they occur in glacimarine deposits (Nelson et al., 2009). Jonkers et al. (2002) believed this was a function of minimal transport with the bivalves preserved virtually *in situ*. *Austrochlamys* of the Hobbs Glacier and Cockburn Island formations belong to the species *A. anderssoni* (see Jonkers, 2003), thought to be a byssally attached epibenthic form (Berkman et al., 2004, p. 1845). Although these bivalves are believed to have occupied water depths not greater than 100 m (Jonkers, 1998a; Jonkers et al., 2002), sometimes they occur as transported fragmentary specimens in strata that may have been deposited at greater water depths (Jonkers et al., 2002, p. 586).

Austrochlamys is a significant indicator of palaeoenvironment for the Antarctic (Berkman et al., 2004). Modern *Austrochlamys natans* occur in the high energy sub-littoral and littoral zones of southern Chile and Argentina, as far south as Bahia Orange (Dijkstra and Köhler, 2008). Modern sea surface temperatures in southernmost South America range between about 5 to 10°C (NOAA monthly global SST plot archive at: http://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/). As well as living at shallow depths *Austrochlamys* is recovered from greater depths, and for example the holotype of *A. natans* was recovered from 125 m in the Magellan Strait (see Dijkstra and Marshall, 2008). Seawater temperatures in southernmost South America (between 52 to 56°S) at depth 125 m range between about 4 to 8°C annually, and at 500 m are between 4 to 6°C (NODC

World Ocean Atlas, Monthly Mean one degree sea temperatures at: http://apdrc.soest.hawaii.edu/las/servlets/dataset). Berkman et al. (2004) have argued that the presence of *Austrochlamys* in Antarctic fossil assemblages suggests similar conditions to modern southernmost South America, and in particular, much reduced sea ice extent. Jonkers (1998a) also suggested a sea ice free environment for the Cockburn Island Formation, based on the presence of barnacles in his littoral facies and the absence of ice-rafted debris. Opal depositional rates, which are linked to biological productivity, are conspicuously enhanced in the Early Pliocene, between 5.2 and 3.1 Ma, signifying much-reduced sea ice cover (Hillenbrand and Fütterer, 2002; Pudsey, 2002). Although microfossil assemblages found in the ODP Leg 178 drift sediments show no evidence of significantly warmer surface water temperatures than today (Hillenbrand and Fütterer, 2002), Hepp et al. (2006) have suggested open ocean conditions in the warm Early Pliocene, even during glacials. In addition, diatom evidence from ODP site 1165 (in the Southern Ocean at 64.384°S) reported by Whitehead and Bohaty (2003) gives mean annual temperatures at 4°C, and the absence of ice-rafted debris in the Cockburn Island Formation (Jonkers, 1998a) also suggests warmer conditions than present.

Modern coastal environments of James Ross Island and other Antarctic regions, where seasonal sea ice is prevalent, are characterised by the slow-growing, thin-shelled scallop *Adamussium colbecki* (Berkman et al., 2004). This bivalve is thought to have originated in deeper water and to have migrated on to the shelf as conditions cooled during the Late Pliocene. *Adamussium colbecki* lives below sea ice, in conditions that mimic the deep ocean. It effectively replaced *Austrochlamys* as the dominant scallop, which retreated across the Southern Ocean to South America (Berkman et al., 2004). Thus, *Austrochlamys* may provide a proxy of reduced sea ice conditions and more agitated coastal waters around James Ross and Cockburn islands during the Pliocene, a hypothesis that we will test in this paper by examining the growth-increment pattern and geochemical signature of fossil shells.

5. Methodology: analysis of bivalve material

Our methodology to understand the growth and habitat of fossil *Austrochlamys* in the Cockburn Island Formation uses three lines of evidence: oxygen isotopes to determine seasonality and the approximate temperature of the water in which the bivalves were living; carbon isotopes to determine metabolic rates and food supply during growth; and growth increments to assess the pattern of growth. Relating these different data sources is a means of providing a detailed picture of the environmental setting of *Austrochlamys* in the late Neogene coastal waters of the Antarctic.

5.1 Geochemical analyses

Only well-preserved fossil material has been analysed. Neogene shells of *Austrochlamys* from the Antarctic Peninsula that we interpret as being pristine show no variation in composition that is detectable under Scanning Electron Microscopy (with EDX analysis). With the exception of a few specimens, the shell lamellae have no visible cement overgrowths or recrystallisation. The calcitic shell lamellae (confirmed by XRD analysis of 3 shell fragments) are non-luminescent to weakly luminescent under cathodoluminescence, indicating no diagenetic cements are present. One specimen has a diagenetic cement overgrowth on the external surface of the valve as bladed calcite crystals, which are strongly luminescent (Fig. 4), and this specimen has been excluded from the isotopic analysis. Many shells have a fine layer of carbonate-cemented clay material adhering to the outer surface of the shell. Before drilling for geochemical analysis, this extraneous material was removed by gentle scrubbing and immersion of the shell in a bath of 5% HCl followed by washing with de-ionised water. After this treatment the shells looked pristine with the majority of the sediment removed and the growth increments clearly showing. The growth increments of *Austrochlamys* are large and easy to drill and it is possible to obtain sufficient material from each, whilst avoiding remaining adherent sediment. Shells representing several years of growth (e.g. DJ.851.159, DJ.851.160 and DJ.853.1) were selected for analysis. Some 250 growth increments from three shells have been sampled for calcite and analysed for stable carbon and oxygen isotopes

(Figs 3, 6). Approximately 30-100 micrograms of carbonate have been used for each isotope analysis using a GV IsoPrime mass spectrometer plus Multiprep device. Isotope values ($\delta^{13}C$, $\delta^{18}O$) are reported as per mil (‰) deviations of the isotopic ratios ($^{13}C/^{12}C$, $^{18}O/^{16}O$) calculated to the VPDB scale using a within-run laboratory standard calibrated against NBS standards. Analytical reproducibility of the standard calcite (KCM) run with these samples was 0.02‰ for $\delta^{13}C$ and 0.04‰ for $\delta^{18}O$. Values for oxygen isotopes have been converted to sea palaeotemperatures using the equation of O'Neil et al. (1969), $T = 16.9 - 4.38(\delta^{18}O_c - \delta^{18}O_{sw}) + 0.10(\delta^{18}O_c - \delta^{18}O_{sw})^2$. A. Johnson et al. (2000) have demonstrated good calibration between actual sea temperatures and reconstructed sea temperatures using this equation applied to North Sea modern and sub-fossil *Aequipecten*. For comparison we have also calculated palaeotemperatures using a modified form of the Craig (1965) equation given in Leng and Marshall (2004), $T = 16\text{-}4.14(\delta^{18}O_c - \delta^{18}O_{sw}) + 0.13(\delta^{18}O_c - \delta^{18}O_{sw})^2$: typically this makes palaeotemperature estimates warmer by about 0.5 to 0.8°C (see Table 1).

5.2 Assessing seawater isotopic composition

Implicit in calculations of palaeotemperature from the $\delta^{18}O$ of *Austrochlamys* calcite is an assessment of the isotopic composition of the seawater ($\delta^{18}O_{sw}$) in which the bivalves were living. Surface seawater $\delta^{18}O$ in the Weddell Sea today is between 0 and –0.5‰ (Schmidt et al., 1999). Mackensen (2002) gives a mean value of –0.37‰ for Antarctic Surface Water in the southern Weddell Sea. Oceanographic conditions in the Weddell Sea have been summarized by Whitehouse et al. (1996), who showed summer to winter temperature variation between +1.99 and –0.10°C, with salinity greater in winter time (33.87 to 34.05 psu) than in summer (33.81 to 33.86 psu). The flux of isotopically light glacial meltwater into the northern Weddell Sea around James Ross Island during the summer months affects the $\delta^{18}O$ of surface water. Although there are no detailed studies of meltwater flux around James Ross Island, these effects are well constrained for surface water on the western Antarctic Peninsula region in Marguerite Bay at 68˚S (Meredith et al., 2008). The

setting of Marguerite Bay is different from that of the Weddell Sea in that $\delta^{18}O_{sw}$ values in the western peninsula region are lower for surface waters (between –0.5 to –1‰; see Schmidt et al., 1999). However, the north end of Marguerite Bay is covered by winter sea ice for several months, so that it provides a useful comparison for seasonal fluxes of sea ice and glacial meltwater into the modern James Ross Island area, where sea ice also forms during the winter months. In Marguerite Bay as much as 5% of the near-surface ocean is glacial meltwater: sea ice-melt accounts for a much smaller percentage (*ca* 1%). The effects of seasonal sea ice-melt on the $\delta^{18}O_{sw}$ are minimal (Meredith et al., 2008, p. 314) but those of glacial ice-melt are much more significant as high latitude ice has very low $\delta^{18}O$ (Mackensen, 2002; Meredith et al., 2008). In Marguerite Bay surface waters are isotopically lightest during the summer months, with values as low as –0.9‰ (compared with higher values of –0.1‰ for deeper water below 300 m). During winter months the $\delta^{18}O$ of surface waters is about –0.5‰, still much lower than deeper waters and indicating that significant quantities of meteoric water remain in the upper water column throughout the year.

Our estimates of palaeotemperature from *Austrochlamys* have assumed an initial surface $\delta^{18}O_{sw}$ value of –0.2‰. This is a mean value sourced from a climate model study of the Early Pliocene (Lunt et al., 2008) and is similar to modern surface conditions in the Weddell Sea (Schmidt et al., 1999; Mackensen, 2002). For calculations of $\delta^{18}O_{sw}$ from the model see Appendix 1. There is considerable evidence for the persistence of an Antarctic Peninsula Ice Sheet even during warm phases of the late Neogene (Smellie et al., 2009; J. Johnson et al., 2009; Nelson et al., 2009), though sea ice cover in this region may have been much more limited (Berkman et al., 2004). Thus, fluxes of meltwater such as those into Marguerite Bay may have characterized the northern Weddell Sea region during warm interval summers, and may have kept surface waters isotopically light throughout the year, with $\delta^{18}O$ values lowest during the summer. For this reason, we have also calculated palaeotemperatures using higher and lower values of $\delta^{18}O_{sw}$ (0 to –0.4‰) to reflect seasonal (winter-summer) variation (see Table 1).

5.3 Growth increment analysis

Austrochlamys grows by a series of increments that are visible on the shell surface (Fig. 3). These increments result from the advance of the mantle over the ventral margin to effect extension of extrapallial fluid and precipitation of calcite to the shell edge. In scallops, as in other bivalves, large-scale mantle advance and shell-size increase is dependent on the environmental conditions which facilitate cell division and growth. However, under such conditions, shell extension is fairly regularly interrupted for short periods through retraction of the mantle edge, resulting in an incremental pattern of shell growth which is clearly marked by commarginal ridges on the external surface (Clark, 1974, 2005). The individual (microgrowth) increments may be over 1 mm in width in *Austrochlamys* (Fig. 5), which is exceptionally large amongst scallops (cf. Clark, 2005; Owen et al., 2002b; A. Johnson et al., 2009). Overall periods of growth may be succeeded by sudden and sharp reductions in calcite precipitation, and the shell is therefore marked by a distinct band known as a 'growth line'. These lines may represent suspension of growth associated with seasonal temperature extremes, wave action, reproduction (Dame, 1996, p. 58) or disturbance (e.g. Adam, 1990). In *Austrochlamys* from the Cockburn Island Formation growth lines are developed on many shells with varying degrees of prominence (Fig. 3).

To measure growth increments precisely, scaled photographic images of *Austrochlamys* were imported into the software Panopea (© Peinl and Schöne, 2004). This enables point-to-point measurements of growth increment widths and reference features, and outputs a precise width of these structures. The factors behind the rate of growth of *Austrochlamys* cannot be differentiated by growth increments alone (see Jones and Quitmyer, 1996), but coupled to $\delta^{13}C$ and $\delta^{18}O$ profiles (see A. Johnson et al., 2000, 2009) it is possible to make inferences about control mechanisms such as food supply and water temperature.

6. Results and interpretation

6.1 Oxygen isotopes and palaeotemperature

The three shells we have analysed for stable isotopes collectively record about seven summer-winter cycles of growth (Fig. 6), with an overall reconstructed temperature range from -1 to +3.5°C (using the O'Neil et al., 1969 equation), or slightly higher minimum and lower maximum temperatures if higher winter and lower summer $\delta^{18}O_{sw}$ values are used (Table 1). We do not suggest that this represents the entire range of climate for the Cockburn Island Formation, but it does provide the first quantifiable evidence of sea temperature seasonality for about seven years in this region from the late Neogene. The two shells from locality DJ.851 show similar temperature profiles, while that from locality DJ.853 shows the warmest summer values (Fig. 6, Table 1). These two bivalve-bearing localities are separated by about 300 m along a north-south transect on the east side of the island (Fig. 2) and while the bivalves are from the same substratum, they may represent molluscs living 100s of years apart.

Isotope analysis of shell DJ.851.159 shows a signal of seasonality in water temperature over three cycles of summer-winter growth (Fig. 6). During this interval (using an annual mean $\delta^{18}O_{sw}$ of –0.2‰ and the O'Neil et al., 1969 equation), sea temperatures between –1.1 and +2.5°C are suggested. This range of temperature variation (*ca* 3.6°C) is similar to the present mean intra-annual range in surface waters of the Weddell Sea (see Whitehouse et al., 1996). It is also similar to the seasonal temperature variation at the sea surface predicted by an Early Pliocene climate model, giving values of –1.69°C for winter (July) and +3.08°C for summer (February) at depth 0-5 m (Lunt et al., 2008). At depth (95-113 m) seasonality from the model is just –0.69 to –0.52°C. This supports the notion that the *Austrochlamys* of the Cockburn Island Formation were living at shallow depth, recording much of (or the entire) surface seasonality, and were well above the maximum depth of 100 m speculated on by Jonkers et al. (1998a, 2002).

The use of a single mean annual value for $\delta^{18}O_{sw}$ in our calculations shown in Figure 6 may be unjustified (and lead to over- or underestimates of palaeotemperature) in that it assumes no large change in glacial meltwater flux to this region of the northern Weddell Sea between summer and winter. Calculating sea temperatures for shell DJ.851.159 using a winter value of 0‰ for $\delta^{18}O_{sw}$

gives a minimum water temperature of –0.4°C, close to that recorded today. Using a summer value of –0.4‰ for $\delta^{18}O_{sw}$ gives a maximum temperature of about 2°C (Table 1). This seasonal range in $\delta^{18}O_{sw}$ is justified by modern data from Marguerite Bay (see Meredith et al., 2008 and above).

Forty analyses from shell DJ.851.160 produce estimated sea temperatures similar to those of shell DJ.851.159, with a minimum just below 0°C and a maximum of 1.8°C (for $\delta^{18}O_{sw}$ = -0.2‰, see Fig. 6, see also Table 1). In contrast, shell DJ.853.1, which also records about three cycles of summer-winter growth (*ca* 100 increments drilled), provides sea temperatures between 0.5 and 3.5°C (for $\delta^{18}O_{sw}$ = -0.2‰, Fig. 6). Given that these shells are from two different localities, the latter hints that a very detailed record of changing regional climate may be stored in these fossils.

Modern temperature beneath the sea ice during winter months in the Weddell Sea is close to 0˚C (Whitehouse et al., 1996; cf. with similar sea temperatures in Marguerite Bay reported by Meredith et al., 2008, p. 312), suggesting that our estimates of winter temperature in shells from locality DJ.851 may be too cool for the Early Pliocene. Although the overall degree of seasonal sea temperature change appears similar to present (Table 1), we cannot be sure that our reconstructed temperatures reflect absolute values. However, given a winter temperature of –1.1°C from bivalve DJ.851.159, they must represent near minimum values. Recalculating palaeotemperatures using the modified form of the 'Craig (1965)' equation (see Table 1) gives a slightly elevated minimum temperature of -0.3ºC for shell DJ.851.159, close to the modern minimum values recorded by Whitehouse et al. (1996).

As well as the problem of assessing initial $\delta^{18}O_{sw}$ some bivalves are known to exhibit vital effects. Thus, experimental work on *Pecten maximus* shows deviations of shell $\delta^{18}O$ from equilibrium of +0.6‰, equivalent to a temperature interpretation 2-3°C colder than actual (Owen et al., 2002a). With our available data we cannot assess whether vital effects have influenced the $\delta^{18}O$ of *Austrochlamys* calcite, but it is feasible that our minimum and maximum estimates of sea temperature are colder than actual, and that sea temperatures were above zero throughout the year at the time the Cockburn Island Formation was being deposited. This is suggested by sea temperature

values from the shell at locality DJ.853 that show a minimum above 0ºC (Fig. 6, Table 1), and by our growth increment data (see below).

6.2 Carbon isotopes and planktonic productivity

The $\delta^{13}C$ signature of bivalves is influenced by the isotopic composition of the dissolved inorganic carbon (DIC) in seawater, its major controls being local phytoplankton productivity (removing ^{12}C), local respiration (returning ^{12}C) and influxes of isotopically more negative deep ocean water or freshwater (Krantz et al., 1987). Thus, bivalves living close to upwelling zones can exhibit marked changes in $\delta^{13}C$ (Jones and Allmon, 1996) whereas those living away from such zones may exhibit a much smaller degree of variation, less than 1‰ (A. Johnson et al., 2000, 2009). The $\delta^{13}C$ may also reflect a kinetic effect. This results in a depletion of both ^{18}O and ^{13}C in carbonates (McConnaughey et al., 1997; Owen et al., 2002a). In contrast, metabolic (respiration) effects will be reflected in depletions in shell $\delta^{13}C$ (McConnaughey and Gillikin, 2008) which are not accompanied by simultaneous changes in shell $\delta^{18}O$. Thus, the two mechanisms can be differentiated in isotopic profiles of bivalves.

The carbon isotope signature of *A. anderssoni* suggests both metabolic and oceanographic controls, but not kinetic effects. Carbon isotope values are lowest through the first annual cycle of temperature variation recorded in shell DJ.851.159 (*ca* 1.4‰), perhaps related to high metabolic rate in a young specimen. The carbon signature is a little higher through the second cycle of temperature variation recorded in shell DJ.851.159 (*ca* 1.7‰), and then is variable into the third cycle (from *ca* 1.2 to nearly 2‰). However, the two peaks of highest carbon values (at about 2‰) correlate with summer temperature maxima determined from analysis of $\delta^{18}O$ (Fig. 6), and suggest a phytoplankton control, influenced by a summer bloom. There are no areas of the shell DJ.851.159 profile where oxygen and carbon show depletion in tandem, and we interpret this as being evidence of minimal or no kinetic effects. A very similar pattern of highest $\delta^{13}C$ (about 2‰) associated with summer temperature is also preserved in shell DJ.851.160 (Fig. 6). Peak highest values of $\delta^{13}C$ also

coincide with warmest estimated sea temperatures in bivalve DJ.853.1. Here though, peak highest $\delta^{13}C$ values (of 2.4‰) are greater than in the two bivalves from locality DJ.851, suggesting that increased water column productivity might have been influenced by the warmer overall temperatures apparently experienced by bivalve DJ.853.1.

Conceivably, more upwelling of deep ocean water in winter-time could produce the characteristic low $\delta^{13}C$ patterns that correlate with the highest $\delta^{18}O$ in the three shells analysed (Fig. 6). Differences in wind strength between summer (weaker) and winter (stronger) could account for this, but these differences could not have had an effect if the sea was ice-covered in winter.

6.3 Growth increments and the availability of benthic food

All of the bivalves measured show patterns in growth involving clusters of broader and narrower increments (Fig. 5). The initial (umbonal) region of each shell bears increments which are too narrow or ill-defined to be measured (Fig. 3). This is typically over the first 2-3 cm of well-preserved shells. Thus, we have been unable to assess growth patterns for the earliest stages of development in *Austrochlamys* and it should be noted that the graphs do not represent the same growth increment interval between bivalves (see Fig. 3 for position of growth measured on each shell). For those increments that can be measured, there is a wide range of variation in width both within and between shells, varying from 0.09 mm (DJ.852.1) to *ca* 1.7 mm (DJ.851.3). Some specimens clearly have broader growth increments overall: thus, 5 cm of shell growth can be achieved over 60 (e.g. DJ.851.3), 76 (DJ.851.80) or 93 increments (DJ.851.159). The number of increments between a peak and a trough in the growth of *Austrochlamys* varies from about 3 to 14, with no discernible increase in frequency from younger to older specimens (Fig. 5). Notwithstanding the growth lines that represent probable growth breaks, analysis of growth cumulatively suggests that while *Austrochlamys* is growing, growth rate remains similar, with no significant reduction during colder periods (see Fig. 6).

366 The annual cycles in environmental variables (e.g. sea temperature and phytoplankton
367 productivity) determined from stable oxygen and carbon isotope analyses correspond to growth
368 intervals involving from 24 to 38 increments on shell DJ.851.159, with winter troughs at increments
369 19, 57 and beyond 81 (and summer highs at increments 1, 39 and 75 respectively). The winter-
370 summer signal from the isotopes is clearly independent of the growth variation exhibited by the
371 increments, which have a much higher frequency of change (Fig. 6) and were likely controlled by
372 other factors. In addition, the seasonal temperature signal does not appear to bear any close
373 relationship to the distinctive growth lines of shell DJ.851.159, at least one of which appears to be
374 associated with marginal shell damage (see Figs 3, 6) and therefore perhaps disturbance. Shell
375 DJ.851.160, from the same locality as DJ.851.159, confirms this pattern, with growth increment
376 variation of similar degree in both summer and winter, and a growth line in the part of the shell
377 drilled for stable isotopes which is synchronous with rising temperatures, probably towards the end
378 of a winter cycle (Fig. 6).

379 In contrast shell DJ.853.1, from the northern-most pectinid-bearing locality on Cockburn
380 Island (Fig. 2) shows a different pattern of growth to those shells from locality DJ.851. In this shell
381 two growth lines do equate to intervals of temperature lows (Fig. 6), though not to the final low
382 temperature interval (beyond increment 90). From increment 1 to 59 there is no apparent summer-
383 winter variation in overall growth rate when the bivalves are growing, with peaks and troughs in
384 increment width occurring with a higher frequency than the peaks and troughs in temperature
385 variation (fig. 6). The first weak growth line appears to come towards the end of a winter cycle, and
386 is associated with a temperature low. But this growth break appears to have been of short duration
387 as there is a substantial interval of winter prior to this (Fig. 6). It occurs in that part of the shell
388 where the $\delta^{13}C$ signal indicates a rapid increase in water column productivity, and therefore the
389 growth line probably formed at, or just prior to the beginning of spring-summer. The second growth
390 line, beginning at about increment 58, is stronger and corresponds to a temperature low. Here there
391 is clear evidence for a slowing of growth (from increment size measurements, Fig. 6), and this part

of the shell is also associated with a rapid change to lower $\delta^{13}C$ that may record the onset of winter. The isotope record is missing through about 5 to 6 increments as these were too narrow to drill, and so the winter temperature minimum has not been determined. The increments immediately following the growth line show rapid temperature rise into summer (Fig. 6). Nevertheless, the temperature low associated with this growth line (and apparent growth cessation) was well above zero at the time growth slowed (Fig. 6), and is in line with winter temperature values elsewhere in this shell where growth continued. We therefore suggest that this growth break might be associated with shell disturbance, rather than with growth cessation from low temperature. Shell DJ.853.1 records a second season of summer growth with a maximum estimated temperature of 3.5°C at increment 72, and a final period of presumed winter growth with temperatures about 1.5°C beyond increment 88 (Fig. 6). There is no distinctive growth line associated with the beginning of this last interval of 'cooler' temperatures, and increment analysis indicates that growth continued at a similar pace irrespective of whether temperatures were 'warm' or 'cool' (Fig. 6).

Conventional wisdom interprets the growth patterns of bivalves in terms of summer to winter variation, but Jones and Quitmyer (1996) have demonstrated convincingly that there may be a decoupling between growth rate and temperature in bivalves. The growth-increment patterns in the shells analysed for stable isotopes from the Cockburn Island Formation (Figs 3, 6) are closely comparable to those of Holocene *Aequipecten* from the North Sea (A. Johnson et al., 2009) – that is, there is no seasonal pattern that can be tied with the palaeotemperature profile reconstructed from stable oxygen isotope evidence. Neither is there any correspondence to the pattern of planktonic productivity inferred from carbon isotope evidence. In natural populations of the scallop *Aequipecten* growth is probably tied with benthic food supply, particularly with the availability of detrital organic material. This increases during periods of water column agitation. Growth in the infaunal bivalve *Arctica* appears to be under a similar control (Schöne et al., 2003, 2005; Witbaard, 1996) and the correlation between increment size in Pliocene *Flabellipecten steamsi* from the Gulf of California and tidal patterns in this area (Clark, 2005) is also accountable to re-suspension and

advection of detrital food by tidal currents. In the Weddell Sea, present winter sea ice-cover suppresses movement in the water column during the winter months. Therefore, if sea ice was extensive during the winter months of the Early Pliocene, this would have resulted in reduced agitation of the water column, reduced food supply, and a clear seasonality in growth for *A. anderssoni*. Moreover, there should be less short-term variation in winter than in summer (when the water column would be more agitated), but this is not the case. The growth increment data from *A. anderssoni* is consistent with the proposal of Berkman et al. (2004) that there was reduced (or no) sea ice in Early Pliocene coastal marine settings occupied by *Austrochlamys*. The data also imply that *Austrochlamys* has retreated from the Antarctic as the extent of sea ice grew, probably during cooling in the Late Pliocene to Pleistocene. These Antarctic coastal zones today are colonised by the slow-growing *Adamussium colbecki*, a bivalve that originated in deeper waters that are mimicked by living below sea ice (see Berkman et al., 2004).

7. Marine seasonality and environment on the Antarctic Peninsula during the Early Pliocene

Our data provide a signal of seasonality during warm interglacial phases of Antarctic climate in the late Neogene and allow testing of models of sea ice extent during the Early Pliocene. Growth increment analysis coupled with stable isotope data indicates that sea temperature was not the major influence on growth for *A. anderssoni*. Instead, growth appears to have continued throughout much of the year (even during the coldest parts of winter as recorded in our shells) with a high frequency fluctuation that probably reflects periodic agitation of the water column and enhanced benthic food supply from organic detritus. Such an interpretation differs from the suggestion of Jonkers et al. (2002, p. 587) that the occurrence of *A. anderssoni* in both the Hobbs Glacier (glacial) and Cockburn Island (glacimarine/interglacial) formations indicates its wide environmental tolerance, and that it should therefore not be used solely as an indicator of interglacial (= present-like conditions). Our evidence also suggests that *Austrochlamys* favoured waters that were sea ice-free, and its presence in the Hobbs Glacier Formation may reflect its incorporation into ice toward the

end of an interglacial. Ice-proximal glaciomarine debris flows on James Ross Island incorporated well-preserved bivalves and bryozoans, suggesting that ice expansion occurred under warm conditions during the Pliocene, probably towards glacial inception (Nelson et al., 2009). The presence of bivalves in close proximity to the palaeo-coastline supports the hypothesis of a lack of sea ice, despite the presence of advancing terrestrial-based ice on James Ross Island and the Antarctic Peninsula.

The range of temperatures recorded by the bivalves is similar to the mean annual sea surface temperature range in this region at present (see Table 1). Using the O'Neil et al. (1969) equation, and assuming no vital effects and that our estimates of $\delta^{18}O_{sw}$ approximate reality, the shells that we have analysed show minimum and maximum temperatures to have been between about –1.1 and +2.5°C for the bivalves of locality DJ.851, and temperatures between 0.5 and 3.5°C for locality DJ.853: the temperature range is slightly warmer if we use the modified form of the Craig (1965) equation (see Table 1) with values of -0.3 to 2.8ºC for DJ.851 and 1.1 to 3.7ºC for DJ.853. Our growth increment data, coupled with supporting palaeotemperature information, support: the interpretation of the Cockburn Island Formation as an interglacial marine deposit; the notion of reduced sea ice in the Antarctic during the Pliocene (e.g. Whitehead et al., 2005); and the hypothesis of Berkman et al. (2004) that *Austrochlamys* retreated from the Antarctic as sea ice expanded, this transition occurring during climate cooling in the Late Pliocene. Our bivalve data question climate model predictions of extensive sea ice in the Weddell Sea during the Early Pliocene.

8. Further work

Our work has demonstrated the potential value of *Austrochlamys* for testing hypotheses of seasonality and sea ice extent for pre-Quaternary time slices in the Antarctic. As both the Hobbs Glacier and Cockburn Island formations bear rich bivalve material over a wider stratigraphical range than we have analysed here, there is great scope for developing a highly resolved proxy for

marine palaeoseasonality at these latitudes. Together with the largely unstudied cheilostome bryozoan faunas in the JRIVG – themselves a group of fossils which are excellent proxies for mean annual range of temperature (see Knowles et al., 2009) - a highly resolved record of palaeoclimate through the Late Miocene and Pliocene of the Antarctic Peninsula region may be obtainable.

Acknowledgments

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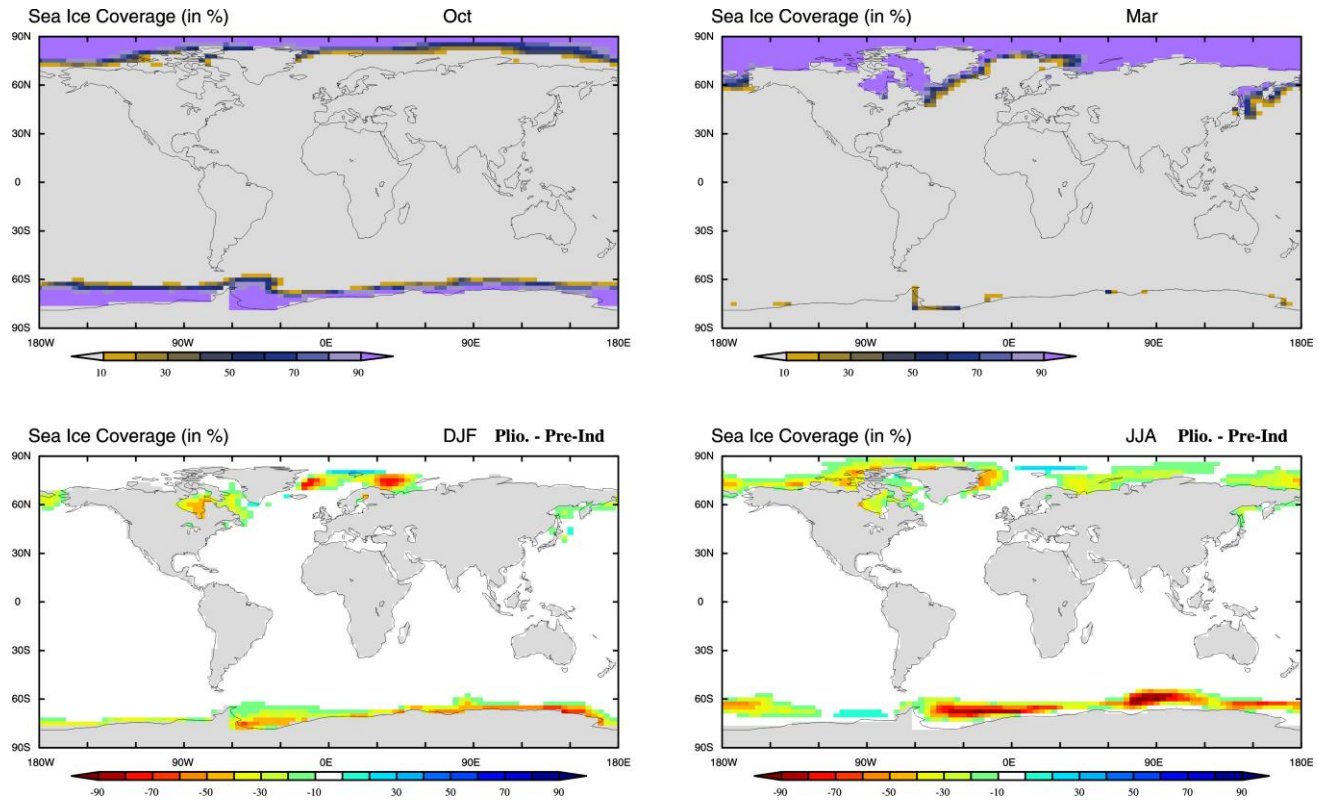
670
671 **Explanation of figures and table**



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673

674 **Fig. 1**. Predictions of absolute sea-ice coverage (%) for maximum (top left) and minimum sea-ice
675 months (top right) in the Southern Hemisphere for the Early Pliocene (data from Lunt et al.,
676 2008). The model predicts sea ice coverage in the northern Weddell Sea at 57°W and 64°S as
677 0.012% cover for late summer rising to 0.908% for late winter. Also shown are the differences
678 between Early Pliocene and pre-industrial sea-ice cover as an average for the Southern Hemisphere
679 summer (December, January and February [DJF; bottom left]) and winter seasons (June, July and
680 August [JJA; bottom right]). Predictions from the Hadley Centre for Climate Research fully
681 coupled ocean-atmosphere General Circulation Model version 3 (HadCM3).

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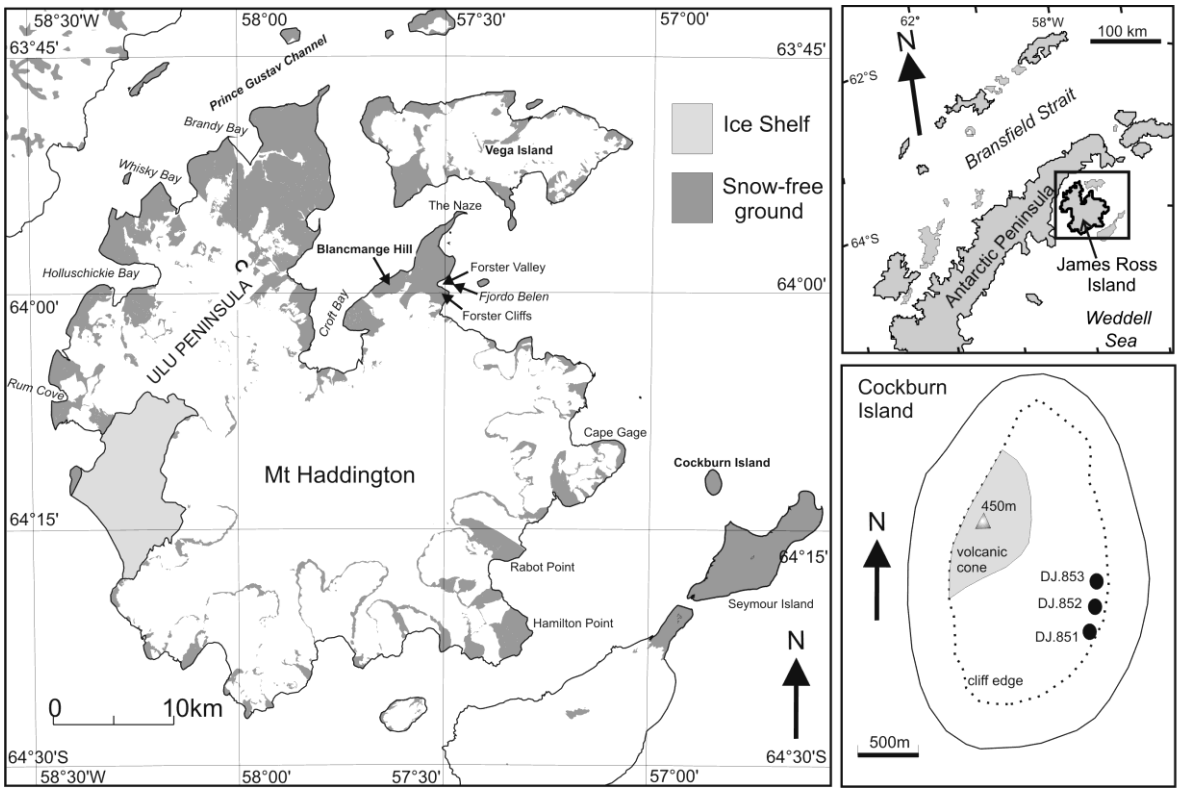

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684

685 **Fig. 2**. Geographical location of James Ross Island on the northern Antarctic Peninsula (top right)
686 and Cockburn Island (see main map to the left). Mollusc material for geochemical and
687 morphological analysis mentioned here is sourced from three localities on the east side of Cockburn
688 Island (map bottom right, localities DJ.851, DJ.852 and DJ.853 of H.A. Jonkers 1996, for which see
689 BAS archives). *Austrochlamys* material is also widespread in the glacigenic sediments of James
690 Ross Island, for example at northwest Forster cliffs.

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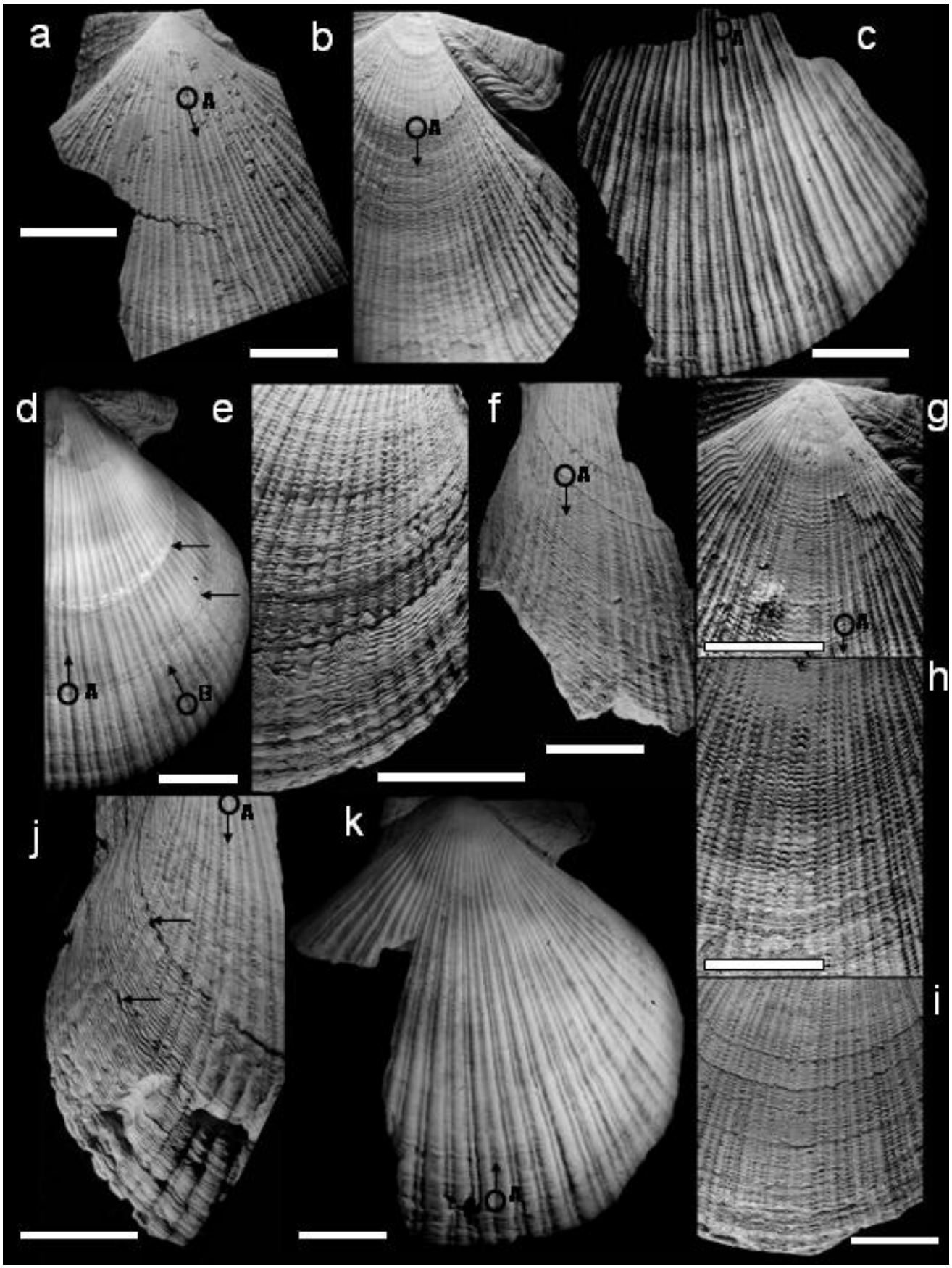
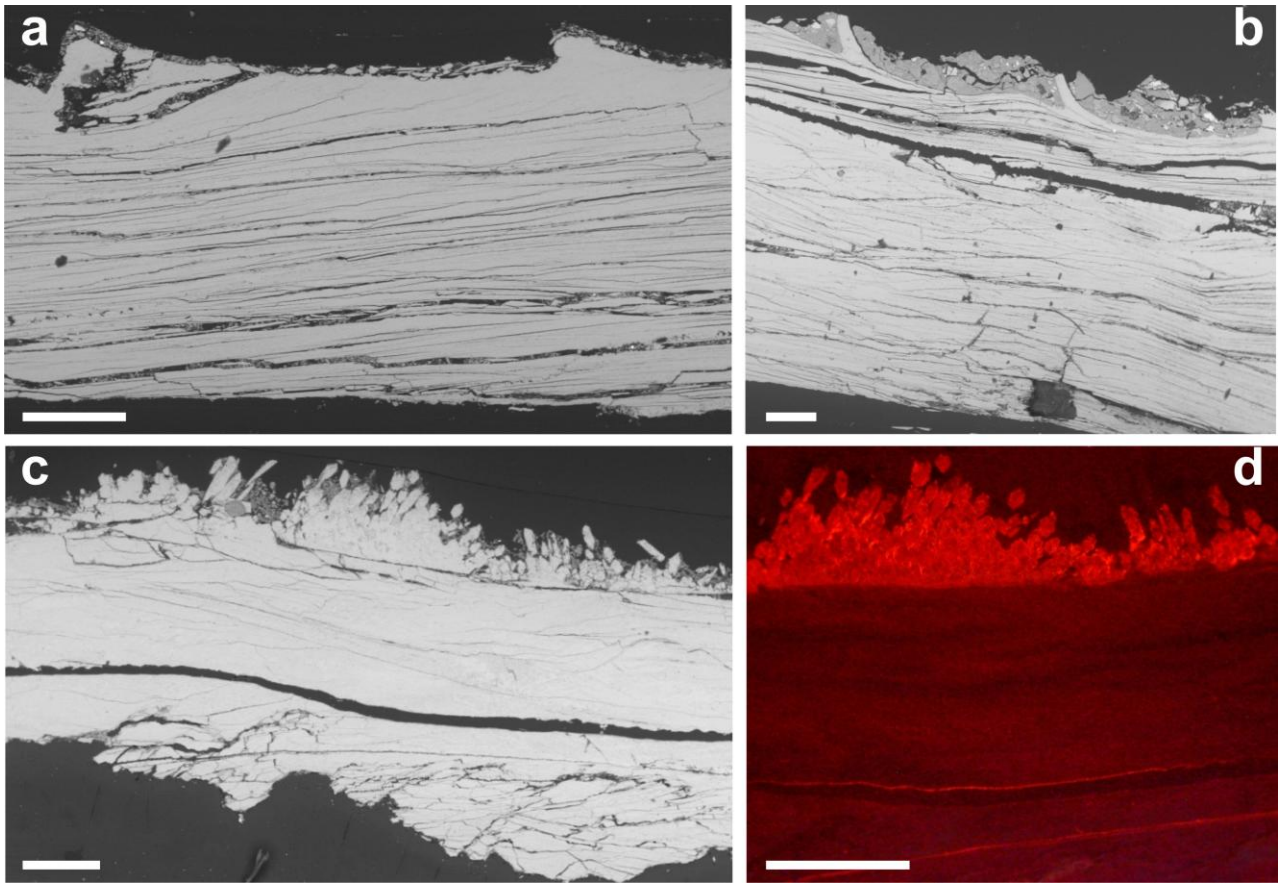


692

693 **Fig. 3**. Morphology of the bivalve *Austrochlamys*. The images are annotated with open circles

694 (labelled ‘A’ or ‘B’) to show points on the shell for cross reference with Figures 4 and 6. The arrow

695 points in the direction where increments were measured. Also arrowed are major growth lines on
696 two of the shells for comparison with the growth/isotope profiles shown in Figure 6. a, right valve,
697 British Antarctic Survey (BAS) DJ.851.8. b, e, right valve, DJ.851.1. c, unnumbered specimen in
698 BAS collection. d, right valve, DJ.853.1. f, left valve, DJ.852.22. g-i, right valve, DJ.851.3. j, right
699 valve, DJ.851.159: bottom right part of image shows damage to the shell possibly as a response to
700 disturbance by a predator. k, right valve, DJ.852.1. All specimens were collected from Cockburn
701 Island by H.A. Jonkers and S.L. White in 1996 (see Fig. 2 for localities) except c, which was
702 collected from surface scree by M. Williams and M. Laidlaw in 2006. Scale bars are 2 cm.
703



704

705 **Fig. 4**. SEM images of polished thin sections of two specimens of Pliocene *Austrochlamys* from the
706 Antarctic Peninsula (a, b). Both images show the well preserved foliated structure of the bivalve
707 shell, but with a thin layer of sediment adhering to the outer surface that was removed prior to
708 geochemical analysis. A specimen with an external diagenetic overgrowth cement of calcite
709 crystals, from the same locality is shown in (c) SEM image, and (d) cathodoluminescence image.

The diagenetic cement is brightly luminescent, while the shell foliae are weakly luminescent. Scale bars are 0.25 mm.

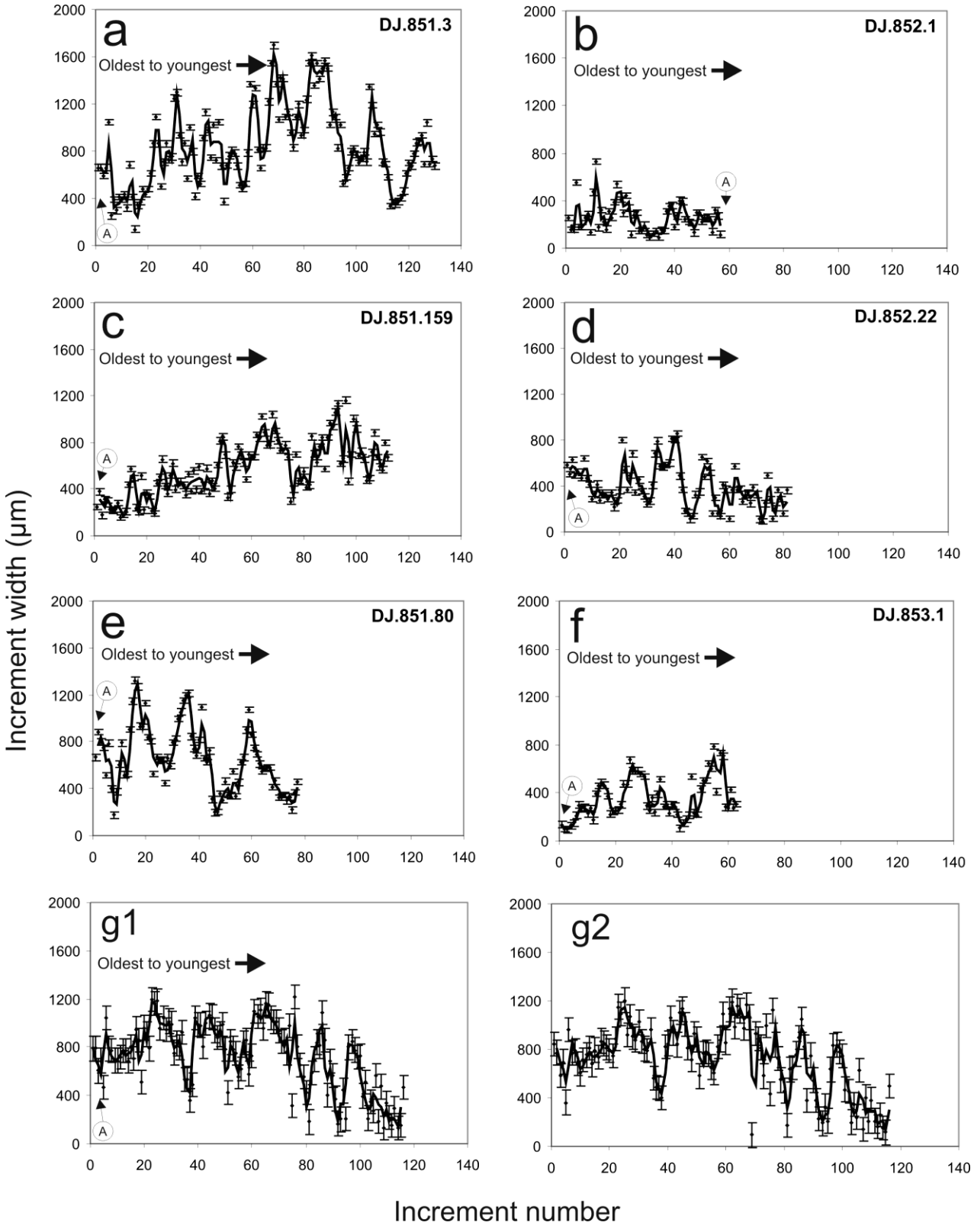
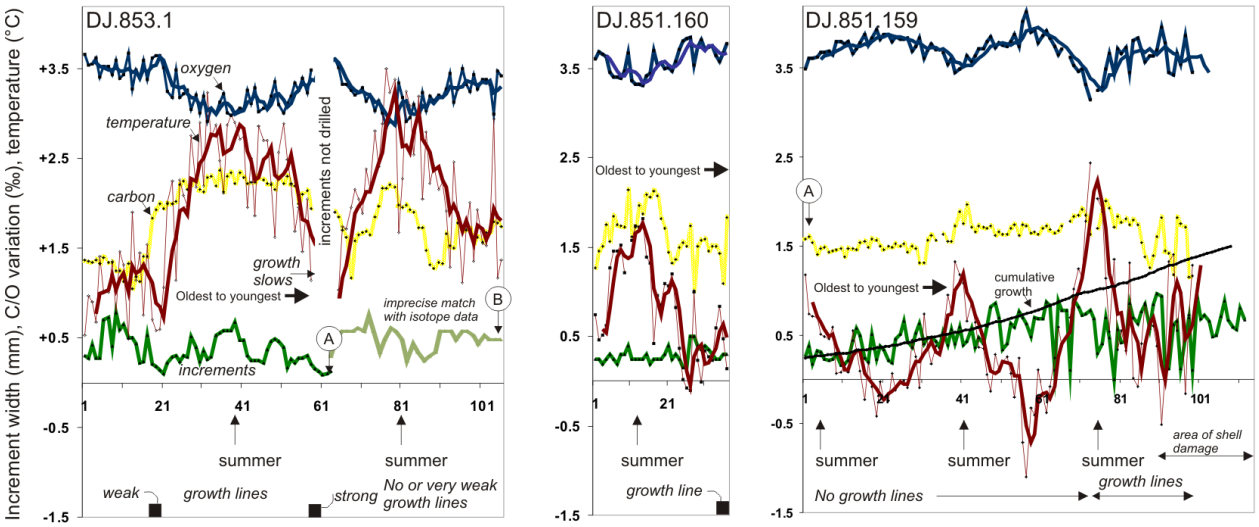


Fig. 5. Growth increment analysis of bivalves from the Cockburn Island Formation. Graphs a-f

715 show growth increments plotted for areas of bivalve shells shown in Figure 3 ('A' denotes points on
716 the shell for cross-reference). Graphs g1 and g2 show repeat measurements for one shell (Fig. 3c)
717 demonstrating the accuracy of measurements that can be achieved with Panopea. Vertical scale is
718 µm, horizontal scale is growth increment measured from oldest (1) to youngest. In addition to the
719 shells plotted here, over 200 increments measured for shell DJ.851.1 show a similar pattern of high-
720 frequency growth variation.
721



722
723 **Fig. 6**. Seasonality recorded in the bivalves DJ.851.159, DJ.851.160 and DJ.853.1 from the
724 Cockburn Island Formation. The figure plots $\delta^{13}C$ (yellow) and $\delta^{18}O$ (blue) as per mil variation (left
725 hand vertical scale). Also shown is temperature (red, left hand scale in °C) reconstructed using a
726 $\delta^{18}O_{sw}$ value of –0.2‰ and the O'Neil et al. (1969) equation [$T = 16.9 – 4.38(\delta^{18}O_c - \delta^{18}O_{sw}) +$
727 $0.10(\delta^{18}O_c - \delta^{18}O_{sw})^2$]; thick red line is the 3-point running average of the temperature
728 reconstruction. The horizontal scale records growth increment number (oldest to left). For all
729 bivalves incremental growth (3-point running average, green, see left hand scale mm variation) is
730 also plotted as is cumulative growth (black line, scale not shown) in bivalve DJ.851.159. 'A' and
731 'B' denote a point on the shell for cross-reference with Figure 3. Also marked are growth lines, with
732 annotation where these may relate to damage (disturbance) on shell DJ.851.159. Precise matching
733 of growth increment measurements with increments drilled for isotopes is not possible, but in most

734 cases we have achieved a match in the data of ± 2 to 3 increments. In shell DJ.853.1 the match
735 between incremental growth and stable isotope values is less precise beyond increment 62 (as
736 indicated by the change to light green colour for the increments).
737

Modern northern Weddell Sea seasonality	Pliocene Modelled seasonality (depth 0-5m)	Pliocene Modelled seasonality (depth 95-113m)	Bivalve DJ.851.159 (δ18Osw of –0.2‰)	Bivalve DJ.851.159 (δ18Osw of –0.2‰) Craig equation	Bivalve DJ.851.159 (δ18Osw variable from 0 to –0.4‰)	Bivalve DJ.851.160 (δ18Osw of –0.2‰)	Bivalve DJ.851.160 (δ18Osw of –0.2‰) Craig equation	Bivalve DJ.851.160 (δ18Osw variable from 0 to –0.4‰)	Bivalve DJ.853.1 (δ18Osw of –0.2‰)	Bivalve DJ.853.1 (δ18Osw of –0.2‰) Craig equation	Bivalve DJ.853.1 (δ18Osw variable from 0 to –0.4‰)
–0.1 to 1.99	–1.7 to 3.08	–0.69 to –0.52	–1.1 to 2.5	–0.3 to 2.8	–0.4 to 2	–0.1 to 1.8	0.6 to 2.3	0.6 to 1.1	0.5 to 3.5	1.1 to 3.7	1.2 to 2.8
2.09	4.78	0.17	3.6	3.1	2.4	1.9	1.7	0.5	3	2.6	1.6

738

739 **Table 1**. Reconstructed sea temperatures from the Cockburn Island Formation bivalves compared
740 with modern and modelled Early Pliocene sea temperature seasonality in the northern Weddell Sea.
741 Modern temperature variation is from Whitehouse et al. (1996), modelled Early Pliocene data is
742 from Lunt et al. (2008). Both temperature maxima and minima and total temperature range are
743 shown. Temperature calculations for 'Craig (1965)' use the form of this equation given in Leng and
744 Marshall (2004) [$T=16-4.14(\delta^{18}O_c - \delta^{18}O_{sw}) + 0.13(\delta^{18}O_c - \delta^{18}O_{sw})^2$] and a $\delta^{18}O_{sw}$ value of -0.2‰.
745

746 **Appendix 1**. Model calculated values for the $\delta^{18}O$ of seawater are an attempt to capture
747 longitudinal and latitudinal change as a function of climate, and are based on precipitation minus
748 evaporation (P − E) estimates derived from the GCM. Present-day observed $\delta^{18}O_{sw}$ [Bigg and
749 Rohling, 2000; Schmidt, 1998, 1999; G. A. Schmidt et al., 1999, Global seawater oxygen-18
750 database, available at http://data.giss.nasa.gov/o18data/] is calibrated against observed P − E
751 (ECMWF reanalysis data) for the Atlantic Ocean. The resulting formulae (see below) are used to
752 predict $\delta^{18}O_{sw}$.
753

754 Atlantic Calibration:
755

756 $\delta^{18}O_{sw} = 0.24 - 0.008\ (P - E)$ r2 = 0.7
757

758 P - E is given in units of cm yr−1.

759

760 Although this is a useful approach, care must be taken when examining the results since they are
761 based solely on the model's predictions of P − E, where in reality the $\delta^{18}O_{sw}$ is also dependent upon
762 mixing because of ocean currents, runoff, etc. The resulting correlation for the Atlantic Ocean
763 $\delta^{18}O_{sw}$ to P − E is reasonable. In addition to P − E we calibrated $\delta^{18}O_{sw}$ against salinity [Levitus and
764 Boyer, 1994]. This increased the r2 value to 0.9 for the Atlantic but Haywood et al. (2007)
765 demonstrated that this did not significantly change the diagnostic predictions of $\delta^{18}O_{sw}$ generated
766 using P – E for the Pliocene.

767 Nevertheless, it is important to recognise that the use of a salinity: $\delta^{18}O$ or P − E: $\delta^{18}O$ co-
768 variation from present-day observations as a diagnostic for the $\delta^{18}O$ composition of seawater is
769 complicated by the fact that temperature gradients are steeper today than they were during the
770 Miocene and Pliocene (a reflection of cooler temperatures in polar regions today) which will result
771 in different patterns of Rayleigh distillation and hence different $\delta^{18}O$ values in the hydrological
772 cycle [Rohling and Bigg, 1998; Rohling, 2000].

773

774