

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

Mark Williams<sup>a,b,\*</sup>, Anna E. Nelson<sup>c</sup>, John L. Smellie<sup>a,c</sup>, Melanie J. Leng<sup>d</sup>, Andrew L.A. Johnson<sup>e</sup>,  
Daniel R. Jarram<sup>a</sup>, Alan M. Haywood<sup>f</sup>, Victoria L. Peck<sup>c</sup>, Jan Zalasiewicz<sup>a</sup>, Carys Bennett<sup>a</sup>, Bernd  
R. Schöne<sup>g</sup>

<sup>a</sup>*Department of Geology, University of Leicester, Leicester, LE1 7RH, UK*

<sup>b</sup>*British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK*

<sup>c</sup>*British Antarctic Survey, Geological Sciences Division, High Cross, Madingley Road, Cambridge, CB3  
0ET, UK*

<sup>d</sup>*NERC Isotope Geosciences Laboratory, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK*

<sup>e</sup>*Geographical, Earth and Environmental Sciences, School of Science, University of Derby, Kedleston Road,  
Derby, DE22 1GB, UK*

<sup>f</sup>*School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK*

<sup>g</sup>*Department of Applied and Analytical Palaeontology, Earth System Science Research Centre, Institute of  
Geosciences, University of Mainz, Johann-Joachim-Becherweg 21, 55127 Mainz, Germany*

\*Corresponding author. E-mail address: [mri@le.ac.uk](mailto:mri@le.ac.uk) (M. Williams)

## Abstract

Growth increment analysis coupled with stable isotopic data ( $\delta^{18}\text{O}/\delta^{13}\text{C}$ ) 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

29

## 30 **1. Introduction**

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

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

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

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

66

## 67 **2. Geological setting**

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

81           The richest Neogene fossil assemblages in the JRIVG are those of the interglacial marine  
82 Cockburn Island Formation, which contains abundant large molluscs, especially *Austrochlamys*  
83 (*Zygochlamys* of Jonkers et al., 2002; see Jonkers, 2003 for a detailed taxonomic appraisal). The  
84 glacimarine deposits of the Hobbs Glacier Formation contain similar macrofossil assemblages, are  
85 dominated by molluscs (including *Austrochlamys*), but also contain older material reworked from  
86 the Cretaceous (Smellie et al., 2006a). Collectively these fossils occur in strata of Late Miocene (ca  
87 6 Ma) through to Pleistocene age (ca 2 Ma). Detailed analysis of the JRIVG has identified three  
88 intervals of relative warmth in the northern Peninsula region, when volcanic rocks were erupted into  
89 a marine environment (Smellie et al., 2006a, fig. 6). Radiometric ( $^{40}\text{Ar}/^{39}\text{Ar}$ ) dates from the  
90 volcanic rocks, together with  $^{87}\text{Sr}/^{86}\text{Sr}$  chronology from the molluscs in the intervening glacimarine  
91 and interglacial marine rocks have produced a well-resolved stratigraphy which constrains the  
92 warm intervals to 6.5 to 5.9, 5.03 to 4.22, and ca 0.88 Ma. The *Austrochlamys* material we study  
93 here, from the second of these warm intervals, is dated at 4.66 +0.17/-0.24 Ma by McArthur et al.  
94 (2006).

95

### 96 **3. Provenance of bivalve material on Cockburn Island**

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

107

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

109 *Austrochlamys* is an epibenthic pectinid bivalve genus comprising six species whose distribution is  
110 restricted to the Antarctic and sub-Antarctic region, with one extant species known from South  
111 America (Jonkers, 2003; Quilty et al., 2004). The earliest *Austrochlamys* occur in Oligocene  
112 deposits of King George Island (for a summary of fossil occurrences see Berkman et al., 2004).  
113 Sub-fossil material is also known from as far north as southern New Zealand (Auckland Islands,  
114 Dijkstra and Marshall, 2008). Fossils of *Austrochlamys* are prolific and widespread in strata of Late  
115 Miocene through Pliocene age of the Hobbs Glacier and Cockburn Island formations and often are  
116 very well preserved (Fig. 3), with specimens articulated even when they occur in glacial marine  
117 deposits (Nelson et al., 2009). Jonkers et al. (2002) believed this was a function of minimal  
118 transport with the bivalves preserved virtually *in situ*. *Austrochlamys* of the Hobbs Glacier and  
119 Cockburn Island formations belong to the species *A. anderssoni* (see Jonkers, 2003), thought to be a  
120 byssally attached epibenthic form (Berkman et al., 2004, p. 1845). Although these bivalves are  
121 believed to have occupied water depths not greater than 100 m (Jonkers, 1998a; Jonkers et al.,  
122 2002), sometimes they occur as transported fragmentary specimens in strata that may have been  
123 deposited at greater water depths (Jonkers et al., 2002, p. 586).

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

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

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

158

## 159 **5. Methodology: analysis of bivalve material**

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

166

### 167 *5.1 Geochemical analyses*

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

185 (Figs 3, 6). Approximately 30-100 micrograms of carbonate have been used for each isotope  
 186 analysis using a GV IsoPrime mass spectrometer plus Multiprep device. Isotope values ( $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$ )  
 187 are reported as per mil (‰) deviations of the isotopic ratios ( $^{13}\text{C}/^{12}\text{C}$ ,  $^{18}\text{O}/^{16}\text{O}$ ) calculated to the  
 188 VPDB scale using a within-run laboratory standard calibrated against NBS standards. Analytical  
 189 reproducibility of the standard calcite (KCM) run with these samples was 0.02‰ for  $\delta^{13}\text{C}$  and  
 190 0.04‰ for  $\delta^{18}\text{O}$ . Values for oxygen isotopes have been converted to sea palaeotemperatures using  
 191 the equation of O'Neil et al. (1969),  $T = 16.9 - 4.38(\delta^{18}\text{O}_c - \delta^{18}\text{O}_{\text{sw}}) + 0.10(\delta^{18}\text{O}_c - \delta^{18}\text{O}_{\text{sw}})^2$ . A.  
 192 Johnson et al. (2000) have demonstrated good calibration between actual sea temperatures and  
 193 reconstructed sea temperatures using this equation applied to North Sea modern and sub-fossil  
 194 *Aequipecten*. For comparison we have also calculated palaeotemperatures using a modified form of  
 195 the Craig (1965) equation given in Leng and Marshall (2004),  $T = 16 - 4.14(\delta^{18}\text{O}_c - \delta^{18}\text{O}_{\text{sw}}) +$   
 196  $0.13(\delta^{18}\text{O}_c - \delta^{18}\text{O}_{\text{sw}})^2$ : typically this makes palaeotemperature estimates warmer by about 0.5 to  
 197 0.8°C (see Table 1).

198

### 199 5.2 Assessing seawater isotopic composition

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



211 setting of Marguerite Bay is different from that of the Weddell Sea in that  $\delta^{18}\text{O}_{\text{sw}}$  values in the  
212 western peninsula region are lower for surface waters (between  $-0.5$  to  $-1\text{‰}$ ; see Schmidt et al.,  
213 1999). However, the north end of Marguerite Bay is covered by winter sea ice for several months,  
214 so that it provides a useful comparison for seasonal fluxes of sea ice and glacial meltwater into the  
215 modern James Ross Island area, where sea ice also forms during the winter months. In Marguerite  
216 Bay as much as 5% of the near-surface ocean is glacial meltwater: sea ice-melt accounts for a much  
217 smaller percentage (*ca* 1%). The effects of seasonal sea ice-melt on the  $\delta^{18}\text{O}_{\text{sw}}$  are minimal  
218 (Meredith et al., 2008, p. 314) but those of glacial ice-melt are much more significant as high  
219 latitude ice has very low  $\delta^{18}\text{O}$  (Mackensen, 2002; Meredith et al., 2008). In Marguerite Bay surface  
220 waters are isotopically lightest during the summer months, with values as low as  $-0.9\text{‰}$  (compared  
221 with higher values of  $-0.1\text{‰}$  for deeper water below 300 m). During winter months the  $\delta^{18}\text{O}$  of  
222 surface waters is about  $-0.5\text{‰}$ , still much lower than deeper waters and indicating that significant  
223 quantities of meteoric water remain in the upper water column throughout the year.

224 Our estimates of palaeotemperature from *Austrochlamys* have assumed an initial surface  
225  $\delta^{18}\text{O}_{\text{sw}}$  value of  $-0.2\text{‰}$ . This is a mean value sourced from a climate model study of the Early  
226 Pliocene (Lunt et al., 2008) and is similar to modern surface conditions in the Weddell Sea  
227 (Schmidt et al., 1999; Mackensen, 2002). For calculations of  $\delta^{18}\text{O}_{\text{sw}}$  from the model see Appendix  
228 1. There is considerable evidence for the persistence of an Antarctic Peninsula Ice Sheet even  
229 during warm phases of the late Neogene (Smellie et al., 2009; J. Johnson et al., 2009; Nelson et al.,  
230 2009), though sea ice cover in this region may have been much more limited (Berkman et al.,  
231 2004). Thus, fluxes of meltwater such as those into Marguerite Bay may have characterized the  
232 northern Weddell Sea region during warm interval summers, and may have kept surface waters  
233 isotopically light throughout the year, with  $\delta^{18}\text{O}$  values lowest during the summer. For this reason,  
234 we have also calculated palaeotemperatures using higher and lower values of  $\delta^{18}\text{O}_{\text{sw}}$  (0 to  $-0.4\text{‰}$ ) to  
235 reflect seasonal (winter-summer) variation (see Table 1).

236

### 237 5.3 Growth increment analysis

238 *Austrochlamys* grows by a series of increments that are visible on the shell surface (Fig. 3). These  
239 increments result from the advance of the mantle over the ventral margin to effect extension of  
240 extrapallial fluid and precipitation of calcite to the shell edge. In scallops, as in other bivalves,  
241 large-scale mantle advance and shell-size increase is dependent on the environmental conditions  
242 which facilitate cell division and growth. However, under such conditions, shell extension is fairly  
243 regularly interrupted for short periods through retraction of the mantle edge, resulting in an  
244 incremental pattern of shell growth which is clearly marked by commarginal ridges on the external  
245 surface (Clark, 1974, 2005). The individual (microgrowth) increments may be over 1 mm in width  
246 in *Austrochlamys* (Fig. 5), which is exceptionally large amongst scallops (cf. Clark, 2005; Owen et  
247 al., 2002b; A. Johnson et al., 2009). Overall periods of growth may be succeeded by sudden and  
248 sharp reductions in calcite precipitation, and the shell is therefore marked by a distinct band known  
249 as a ‘growth line’. These lines may represent suspension of growth associated with seasonal  
250 temperature extremes, wave action, reproduction (Dame, 1996, p. 58) or disturbance (e.g. Adam,  
251 1990). In *Austrochlamys* from the Cockburn Island Formation growth lines are developed on many  
252 shells with varying degrees of prominence (Fig. 3).

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

260

## 261 6. Results and interpretation

### 262 6.1 Oxygen isotopes and palaeotemperature

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

274 Isotope analysis of shell DJ.851.159 shows a signal of seasonality in water temperature over  
275 three cycles of summer-winter growth (Fig. 6). During this interval (using an annual mean  $\delta^{18}\text{O}_{\text{sw}}$  of  
276  $-0.2\text{‰}$  and the O'Neil et al., 1969 equation), sea temperatures between  $-1.1$  and  $+2.5^\circ\text{C}$  are  
277 suggested. This range of temperature variation (*ca*  $3.6^\circ\text{C}$ ) is similar to the present mean intra-annual  
278 range in surface waters of the Weddell Sea (see Whitehouse et al., 1996). It is also similar to the  
279 seasonal temperature variation at the sea surface predicted by an Early Pliocene climate model,  
280 giving values of  $-1.69^\circ\text{C}$  for winter (July) and  $+3.08^\circ\text{C}$  for summer (February) at depth 0-5 m (Lunt  
281 et al., 2008). At depth (95-113 m) seasonality from the model is just  $-0.69$  to  $-0.52^\circ\text{C}$ . This  
282 supports the notion that the *Austrochlamys* of the Cockburn Island Formation were living at shallow  
283 depth, recording much of (or the entire) surface seasonality, and were well above the maximum  
284 depth of 100 m speculated on by Jonkers et al. (1998a, 2002).

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

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

292 Forty analyses from shell DJ.851.160 produce estimated sea temperatures similar to those of  
293 shell DJ.851.159, with a minimum just below  $0^{\circ}\text{C}$  and a maximum of  $1.8^{\circ}\text{C}$  (for  $\delta^{18}\text{O}_{\text{sw}} = -0.2\text{‰}$ ,  
294 see Fig. 6, see also Table 1). In contrast, shell DJ.853.1, which also records about three cycles of  
295 summer-winter growth (*ca* 100 increments drilled), provides sea temperatures between  $0.5$  and  
296  $3.5^{\circ}\text{C}$  (for  $\delta^{18}\text{O}_{\text{sw}} = -0.2\text{‰}$ , Fig. 6). Given that these shells are from two different localities, the  
297 latter hints that a very detailed record of changing regional climate may be stored in these fossils.

298 Modern temperature beneath the sea ice during winter months in the Weddell Sea is close to  
299  $0^{\circ}\text{C}$  (Whitehouse et al., 1996; cf. with similar sea temperatures in Marguerite Bay reported by  
300 Meredith et al., 2008, p. 312), suggesting that our estimates of winter temperature in shells from  
301 locality DJ.851 may be too cool for the Early Pliocene. Although the overall degree of seasonal sea  
302 temperature change appears similar to present (Table 1), we cannot be sure that our reconstructed  
303 temperatures reflect absolute values. However, given a winter temperature of  $-1.1^{\circ}\text{C}$  from bivalve  
304 DJ.851.159, they must represent near minimum values. Recalculating palaeotemperatures using the  
305 modified form of the ‘Craig (1965)’ equation (see Table 1) gives a slightly elevated minimum  
306 temperature of  $-0.3^{\circ}\text{C}$  for shell DJ.851.159, close to the modern minimum values recorded by  
307 Whitehouse et al. (1996).

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

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

317

## 318 6.2 Carbon isotopes and planktonic productivity

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

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

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

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

349

### 350 *6.3 Growth increments and the availability of benthic food*

351 All of the bivalves measured show patterns in growth involving clusters of broader and narrower  
352 increments (Fig. 5). The initial (umbonal) region of each shell bears increments which are too  
353 narrow or ill-defined to be measured (Fig. 3). This is typically over the first 2-3 cm of well-  
354 preserved shells. Thus, we have been unable to assess growth patterns for the earliest stages of  
355 development in *Austrochlamys* and it should be noted that the graphs do not represent the same  
356 growth increment interval between bivalves (see Fig. 3 for position of growth measured on each  
357 shell). For those increments that can be measured, there is a wide range of variation in width both  
358 within and between shells, varying from 0.09 mm (DJ.852.1) to *ca* 1.7 mm (DJ.851.3). Some  
359 specimens clearly have broader growth increments overall: thus, 5 cm of shell growth can be  
360 achieved over 60 (e.g. DJ.851.3), 76 (DJ.851.80) or 93 increments (DJ.851.159). The number of  
361 increments between a peak and a trough in the growth of *Austrochlamys* varies from about 3 to 14,  
362 with no discernible increase in frequency from younger to older specimens (Fig. 5).  
363 Notwithstanding the growth lines that represent probable growth breaks, analysis of growth  
364 cumulatively suggests that while *Austrochlamys* is growing, growth rate remains similar, with no  
365 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  $\delta^{13}\text{C}$  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

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

405 Conventional wisdom interprets the growth patterns of bivalves in terms of summer to  
406 winter variation, but Jones and Quitmyer (1996) have demonstrated convincingly that there may be  
407 a decoupling between growth rate and temperature in bivalves. The growth-increment patterns in  
408 the shells analysed for stable isotopes from the Cockburn Island Formation (Figs 3, 6) are closely  
409 comparable to those of Holocene *Aequipecten* from the North Sea (A. Johnson et al., 2009) – that is,  
410 there is no seasonal pattern that can be tied with the palaeotemperature profile reconstructed from  
411 stable oxygen isotope evidence. Neither is there any correspondence to the pattern of planktonic  
412 productivity inferred from carbon isotope evidence. In natural populations of the scallop  
413 *Aequipecten* growth is probably tied with benthic food supply, particularly with the availability of  
414 detrital organic material. This increases during periods of water column agitation. Growth in the  
415 infaunal bivalve *Arctica* appears to be under a similar control (Schöne et al., 2003, 2005; Witbaard,  
416 1996) and the correlation between increment size in Pliocene *Flabellipecten steamsi* from the Gulf  
417 of California and tidal patterns in this area (Clark, 2005) is also accountable to re-suspension and



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

430

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

432 Our data provide a signal of seasonality during warm interglacial phases of Antarctic climate in the  
433 late Neogene and allow testing of models of sea ice extent during the Early Pliocene. Growth  
434 increment analysis coupled with stable isotope data indicates that sea temperature was not the major  
435 influence on growth for *A. anderssoni*. Instead, growth appears to have continued throughout much  
436 of the year (even during the coldest parts of winter as recorded in our shells) with a high frequency  
437 fluctuation that probably reflects periodic agitation of the water column and enhanced benthic food  
438 supply from organic detritus. Such an interpretation differs from the suggestion of Jonkers et al.  
439 (2002, p. 587) that the occurrence of *A. anderssoni* in both the Hobbs Glacier (glacial) and  
440 Cockburn Island (glacimarine/interglacial) formations indicates its wide environmental tolerance,  
441 and that it should therefore not be used solely as an indicator of interglacial (= present-like  
442 conditions). Our evidence also suggests that *Austrochlamys* favoured waters that were sea ice-free,  
443 and its presence in the Hobbs Glacier Formation may reflect its incorporation into ice toward the

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

450         The range of temperatures recorded by the bivalves is similar to the mean annual sea surface  
451 temperature range in this region at present (see Table 1). Using the O'Neil et al. (1969) equation,  
452 and assuming no vital effects and that our estimates of  $\delta^{18}\text{O}_{\text{sw}}$  approximate reality, the shells that we  
453 have analysed show minimum and maximum temperatures to have been between about  $-1.1$  and  
454  $+2.5^\circ\text{C}$  for the bivalves of locality DJ.851, and temperatures between  $0.5$  and  $3.5^\circ\text{C}$  for locality  
455 DJ.853: the temperature range is slightly warmer if we use the modified form of the Craig (1965)  
456 equation (see Table 1) with values of  $-0.3$  to  $2.8^\circ\text{C}$  for DJ.851 and  $1.1$  to  $3.7^\circ\text{C}$  for DJ.853. Our  
457 growth increment data, coupled with supporting palaeotemperature information, support: the  
458 interpretation of the Cockburn Island Formation as an interglacial marine deposit; the notion of  
459 reduced sea ice in the Antarctic during the Pliocene (e.g. Whitehead et al., 2005); and the  
460 hypothesis of Berkman et al. (2004) that *Austrochlamys* retreated from the Antarctic as sea ice  
461 expanded, this transition occurring during climate cooling in the Late Pliocene. Our bivalve data  
462 question climate model predictions of extensive sea ice in the Weddell Sea during the Early  
463 Pliocene.

464

## 465 **8. Further work**

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

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

474

#### 475 **Acknowledgments**

476 The growth increment analysis of *Austrochlamys* was undertaken by Daniel Jarram as part of his final year Masters  
477 project at the University of Leicester. This work contributes to the British Antarctic Survey's GEACEP Programme  
478 (ISODYN Project - Ice House Earth: Stability or Dynamism), to the British Geological Survey's deep time  
479 palaeoclimate project, and to the SCAR ACE Programme (Antarctic Climate Evolution). We acknowledge support from  
480 the NERC Isotope Geosciences Facilities Steering Committee (grant IP/936/1106). We thank Captain Bob Tarrant and  
481 the officers and crew of HMS *Endurance* for their assistance during the 2006-2007 field season, Mark Laidlaw for field  
482 assistance and Paul Brickle (Falkland Island Fisheries) for supplying sub-fossil material of *Austrochlamys* from the  
483 Falkland Islands. Alistair Crame (BAS) is thanked for permission to analyse the bivalve material geochemically. Colin  
484 Cunningham and Rob Wilson (Leicester) made thin sections and helped with SEM photomicrography, respectively. The  
485 late Tim Brewer ran analyses of shell geochemistry for us and advised on shell preservation. Cheryl Haidon undertook  
486 the XRD analysis of shells. We are especially grateful to Hilary Sloane (NIGL) for assistance with the isotope analysis,  
487 to Arne Ghys (Belgium) for supplying comparative modern *Austrochlamys* material from Tierra del Fuego, and to  
488 Harry Dowsett (USGS) and Daniel Lunt (Bristol) for their constructive reviews. BRS acknowledges financial support  
489 by a DFG (SCHO793/4). This is Geocycles publication number X.

490

#### 491 **References**

- 492 Adam, M.E. 1990. Shell growth in some Nile bivalves. *Journal of Molluscan Studies*, 56, 301-308.
- 493 Berkman, P.A., Cattaneo-Vietti, R., Chiantore, M., Howard-Williams, C. 2004. Polar emergence  
494 and the influence of increased sea-ice extent on the Cenozoic biogeography of pectinid molluscs  
495 in Antarctic coastal areas. *Deep Sea Research Part 2*, 51, 1839-1855.
- 496 Bigg, G. R., Rohling, E.J. 2000. An oxygen isotope data set for marine waters, *Journal of*  
497 *Geophysical Research*, 105, 8527–8535
- 498 Clark II, G.R. 1974. Calcification on an unstable substrate: marginal growth in the mollusk *Pecten*

- 499 diegensis. *Science*, 183, 968-970.
- 500 Clark II, G.R. 2005. Daily growth lines in some living *Pectens* (Mollusca: Bivalvia) and some  
501 applications in a fossil relative: Time and tide will tell. *Palaeogeography, Palaeoclimatology,*  
502 *Palaeoecology*, 228, 26-42.
- 503 Craig, H. 1965. The measurement of oxygen isotope palaeotemperatures. In: Tongiorgi, E. (Ed.),  
504 *Stable Isotopes in Oceanographic Studies and Palaeotemperatures*. Pisa, Consiglio Nazionale  
505 delle Ricerche Laboratorio di Geologia Nucleare, pp. 161–182.
- 506 Dame, R.F. 1996. *Ecology of marine bivalves: an ecosystem approach*. CRC Press: Boca Raton,  
507 Florida. 254 pp.
- 508 Dijkstra, H.H., Köhler, F. 2008. An annotated catalogue of Recent Pectinoidea (Mollusca,  
509 Pectinidae and Propeamussiidae) type material in the Museum of Natural History, Humboldt  
510 University, Berlin. *Zoosystematics and Evolution*, 84, 31-44.
- 511 Dijkstra, H.H., Marshall, B.A. 2008. The Recent Pectinoidea of the New Zealand region (Mollusca:  
512 Bivalvia: Propeamussiidae, Pectinidae and Spondylidae). *Molluscan Research*, 28, 1-88.
- 513 Dowsett, H.M. 2007. The PRISM palaeoclimate reconstruction and Pliocene sea-surface  
514 temperature. In: Williams, M., Haywood, A.M., Gregory, F.J., Schmidt, D.N. (eds.) *Deep-*  
515 *Time Perspectives on Climate Change: Marrying the Signal from Computer Models and*  
516 *Biological Proxies*. The Micropalaeontological Society, Special Publications, The Geological  
517 Society, London, pp. 459-480.
- 518 Epstein, S., Buchsbaum, R., Lowenstam, H.A., Urey, H.C. 1953. Revised carbonate water isotopic  
519 temperature scale. *Geological Society of America Bulletin*, 64, 1315–1326.
- 520 Hambrey, M.J., Smellie, J.L., Nelson, A.E., Johnson, J.S. 2008. Late Cenozoic glacier-volcano  
521 interaction on James Ross Island and adjacent areas, Antarctic Peninsula region. *Geological*  
522 *Society of America Bulletin*, doi: 10.1130/B26242.1.
- 523 Haywood, A.M., Valdes, P.J., Peck, V.L. 2007. A permanent El Niño-like state during the  
524 Pliocene? *Paleoceanography*, 22 (1), doi:10.1029/2006PA001323

- 525 Haywood, A.M., Valdes, P.J., Hill, D.J., Williams, M. 2007. The mid-Pliocene warm period: A  
526 test-bed for integrating data and models. In: Williams, M., Haywood, A.M., Gregory, F.J.,  
527 Schmidt, D.N (eds) Deep time perspectives on climate change: marrying the signal from  
528 computer models and biological proxies. The Micropalaeontological Society, Special  
529 Publications. The Geological Society, London, 443-457.
- 530 Haywood, A.M., Dowsett, H.J., Valdes, P.J., Lunt, D.J., Francis, J.E., Sellwood, B. 2009. Pliocene  
531 climate, processes and problems. *Philosophical Transactions of the Royal Society, Series A*, 367,  
532 3-17.
- 533 Hepp, D.A., Mörz, T., Grützner, J. 2006. Pliocene glacial cyclicality in a deep-sea sediment drift  
534 (Antarctic Peninsula Pacific Margin). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 231,  
535 181-198.
- 536 Hillenbrand, C-D., Fütterer, D.K. 2002. Neogene to Quaternary deposition of opal on the  
537 continental rise west of the Antarctic Peninsula, ODP Leg 178, Sites 1095, 1096, and 1101. In:  
538 Barker, P.F., Camerlenghi, A., Acton, G.D., Ramsay, A.T.S. (eds) *Proceedings of the Ocean  
539 Drilling Programme, Scientific Results*, 178. Texas A and M University, College Station, Texas,  
540 1-40 (CD-ROM).
- 541 Jansen, E., Overpeck, J., Briffa, K.R., Duplessy, J.-C., Joos, F., Masson-Delmotte, V., Olago, D.,  
542 Otto-Bliesner, B., Peltier, W.R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rind, D., Solomina,  
543 O., Villalba, R., Zhang, D. 2007. Palaeoclimate. In: *Climate Change 2007: The Physical  
544 Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the  
545 Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United  
546 Kingdom and New York, NY, USA.
- 547 Johnson, A.L.A., Hickson, J.A., Swan, J., Brown, M.R., Heaton, T.H.E., Chenery, S., Balson, P.S.  
548 2000. The Queen Scallop *Aequipecten opercularis*: a new source of information on late  
549 Cenozoic marine environments in Europe. In: Harper, E.M., Taylor, J.D., Crame, J.A. (eds) *The*

- 550 Evolutionary Biology of the Bivalvia. pp. 425-439. Geological Society of London, Special  
551 Publications 177.
- 552 Johnson, A.L.A., Hickson, J.A., Bird, A., Schoene, B.R., Balson, P.S., Heaton, T.H.E., Williams,  
553 M. 2009. Bivalve sclerochronology and the mid-Pliocene (c. 3.5 Ma) climate of the Southern  
554 North Sea Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, doi:  
555 10.1016/j.palaeo.2009.09.022
- 556 Johnson, J.S., Smellie, J.L., Nelson, A.E., Stuart, F.M. 2009. Did the Antarctic Peninsula Ice Sheet  
557 persist during interglacials? – evidence from cosmogenic dating of Pliocene lavas on James  
558 Ross Island. *Global and Planetary Change*, doi:10.1016/j.gloplacha.2009.09.001
- 559 Jones, D.S., Allmon, W.D. 1995. Records of upwelling, seasonality and growth in stable-isotope  
560 profiles of Pliocene mollusk shells from Florida. *Lethaia*, 28, 61-74.
- 561 Jones, D.S., Quitmyer, I.R. 1996. Marking time with bivalve shells: oxygen isotopes and season of  
562 annual increment formation. *Palaios*, 11, 340-346.
- 563 Jonkers, H.A. 1998a. Stratigraphy of Antarctic late Cenozoic pectinid-bearing deposits. *Antarctic  
564 Science*, 10, 161-170.
- 565 Jonkers, H.A. 1998b. The Cockburn Island Formation; Late Pliocene interglacial sedimentation in  
566 the James Ross Basin, northern Antarctic Peninsula. *Newsletters on Stratigraphy*, 36, 63-76.
- 567 Jonkers, H.A. 2003. Late Cenozoic–Recent Pectinidae (Mollusca: Bivalvia) of the Southern Ocean  
568 and neighbouring regions. *Monographs of Marine Mollusca*, 5, 125 pp.
- 569 Jonkers, H.A., Lirio, J.M., Dell Valle, R.A., Kelley, S.P. 2002. Age and environment of Miocene-  
570 Pliocene glaciomarine deposits, James Ross Island, Antarctica. *Geological Magazine*, 139, 577-  
571 594.
- 572 Knowles, T., Taylor, P.D., Williams, M., Haywood, A.M., Okamura, B. 2009. Pliocene seasonality  
573 across the North Atlantic inferred from cheilostome bryozoans. *Palaeogeography,  
574 Palaeoclimatology, Palaeoecology*, 277, 226-235

- 575 Krantz, D. E., Williams, D. F., Jones, D. S. 1987. Ecological and paleoenvironmental information  
576 using stable isotope profiles from living and fossil molluscs. *Palaeogeography,*  
577 *Palaeoclimatology, Palaeoecology*, 58, 249-266.
- 578 Leng, M.J., Marshall, J.D. 2004. Palaeoclimate interpretation of stable isotope data from lake  
579 sediment archives. *Quaternary Science Reviews*, 23, 811-831.
- 580 Levitus, S., Boyer, T.P. 1994. *World Ocean Atlas 1994*, vol. 4, Temperature, NOAA Atlas  
581 NESDIS, vol. 4, 129 pp., NOAA, Silver Spring, Md.
- 582 Lunt, D.J., Valdes, P.J., Haywood, A.M., Rutt, I. 2008. Closure of the Panama Seaway during the  
583 Pliocene – Implications for Climate and Northern Hemisphere Glaciation. *Climate Dynamics*,  
584 30, 1-18. (doi:10.1007/s00382-007-0265-6).
- 585 McArthur, J.M., Rio, D., Massari, F., Castradori, D., Bailey, T.R., Thirlwall, M., Houghton, S.  
586 2006. A revised Pliocene record for marine-  $^{87}\text{Sr}/^{86}\text{Sr}$  used to date an interglacial event recorded  
587 in the Cockburn Island Formation, Antarctic Peninsula. *Palaeogeography, Palaeoclimatology,*  
588 *Palaeoecology*, 242, 126-136.
- 589 McConnaughey, T.A., Gillikin, D.P. 2008. Carbon isotopes in mollusk shell carbonates. *Geo-*  
590 *Marine Letters*, doi:10.1007/s00367-008-0116-4.
- 591 McConnaughey, T.A., Burdett, J., Whelan, J.F., Paull, C.K. 1997. Carbon isotopes in biological  
592 carbonates: Respiration and photosynthesis. *Geochimica et Cosmochimica Acta*, 61, 611-622.
- 593 Meredith, M.P., Brandon, M.A., Wallace, M.I., Clarke, A., Leng, M.J., Renfrew, I.A., van Lipzig,  
594 N.P.M., King, J.C. 2008. Variability in freshwater balance of northern Marguerite Bay,  
595 Antarctic Peninsula: results from  $\delta^{18}\text{O}$ . *Deep Sea Research Part 2*, 55, 309-322.
- 596 Nelson, A., Smellie, J., Williams, M., Zalasiewicz, J.A. 2008. Late Miocene marine trace fossils  
597 from James Ross Island. *Antarctic Science*, 20, 591-592.
- 598 Nelson, A.E., Smellie, J., Hambrey, M., Williams, M., Vautravers, M., McArthur, J., Regelous, M.  
599 2009. Neogene glacial debris flows on James Ross Island, northern Antarctic Peninsula, and

- 600 their implications for regional climate history. *Quaternary Science Reviews*,  
601 doi:10.1016/j.quascirev.2009.08.016
- 602 O'Neil, J.R., Clayton, R.N., Mayeda, T.K. 1969. Oxygen isotope fractionation in divalent metal  
603 carbonates. *Journal of Chemical Physics*, 51, 5547-58
- 604 Owen, R., Kennedy, H., Richardson, C. 2002a. Experimental investigation into partitioning of  
605 stable isotopes between scallop (*Pecten maximus*) shell calcite and sea water. *Palaeogeography*,  
606 *Palaeoclimatology, Palaeoecology*, 185, 163-174.
- 607 Owen, R., Richardson, C., Kennedy, H. 2002b. The influence of shell growth rate on striae  
608 deposition in the scallop *Pecten maximus*. *Journal of the Marine Biological Association of the*  
609 *United Kingdom*, 82, 621-623.
- 610 Pirrie, D., Crame, J.A., Riding, J.B., Butcher, A.R., Taylor, P.D. 1997. Miocene glaciomarine  
611 sedimentation in the northern Antarctic Peninsula region: the stratigraphy and sedimentology of  
612 the Hobbs Glacier Formation, James Ross Island. *Geological Magazine*, 134, 745-762. doi:  
613 10.1017/S0016756897007796.
- 614 Pudsey, C.J. 2002. Neogene record of Antarctic Peninsula glaciation in continental rise sediments:  
615 ODP Leg 178, Site 1095. In: Barker, P.F., Camerlenghi, A., Acton, G.D., Ramsay, A.T.S. (eds)  
616 *Proceedings of the Ocean Drilling Programme, Scientific Results*, 178. Texas A and M  
617 University, College Station, Texas, 1-40 (CD-ROM).
- 618 Quilty, P.G., Murray-Wallace, C.V., Whitehead, J.M. 2004. *Austrochlamys heardensis* (Fleming,  
619 1957) (Bivalvia: Pectinidae) from Central Kerguelen Plateau, Indian Ocean: palaeontology and  
620 possible tectonic significance. *Antarctic Science*, 16, 329-338.
- 621 Rohling, E. J. 2000. Paleosalinity: Confidence limits and future applications, *Marine Geology*, 163,  
622 1–11.
- 623 Rohling, E. J., Bigg, G.R. 1998. Paleo-salinity and  $\delta^{18}\text{O}$ : a critical assessment, *Journal of*  
624 *Geophysical Research*, 103, 1307–1318

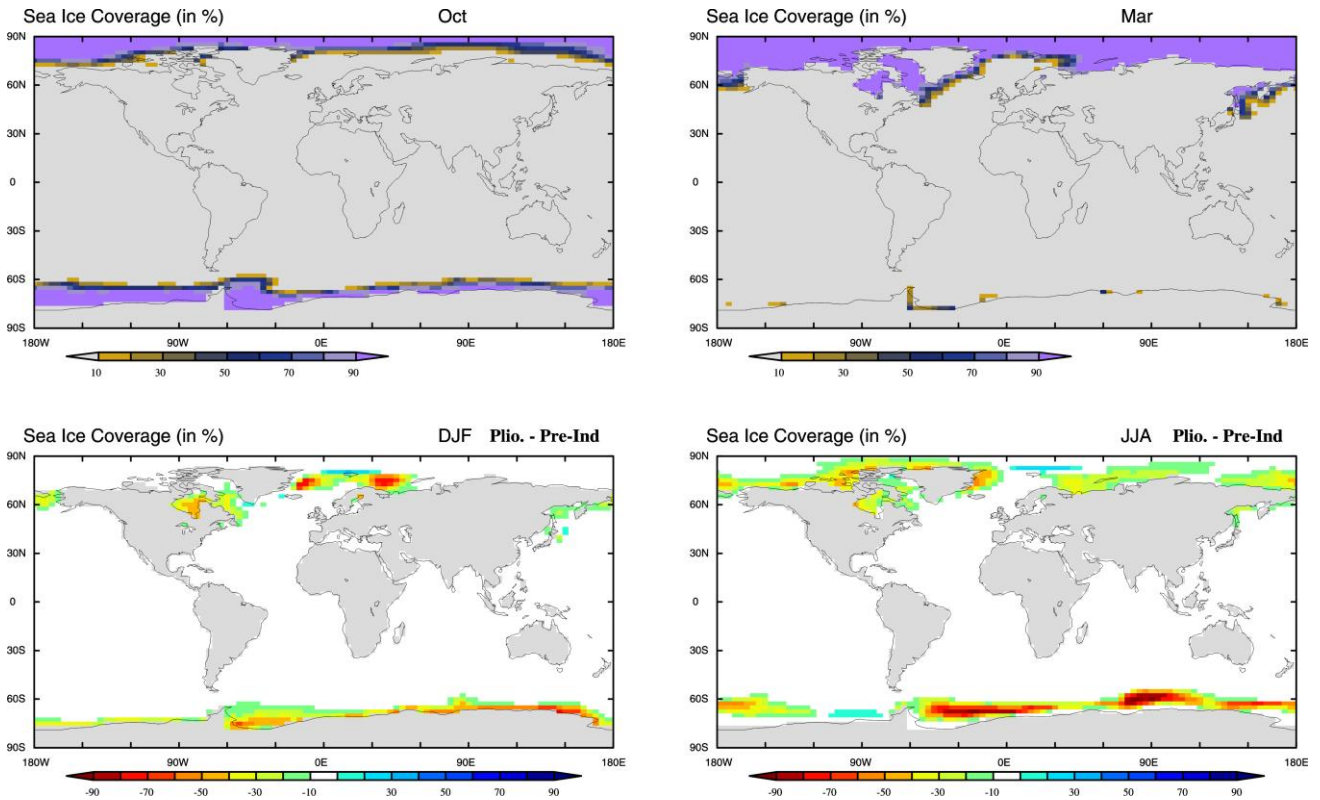


- 625 Schöne, B.R., Oschmann, W., Rössler, J., Freyre Castro, A.D., Houk, S.D., Kröncke, I, Dreyer, W.,  
626 Janssen, R., Rumohr, H., Dunca, E. 2003. North Atlantic Oscillation dynamics recorded in  
627 shells of a long-lived bivalve mollusk. *Geology*, 31, 1037-40.
- 628 Schöne, B.R., Fiebig, J., Pfeiffer, M., Gless, R., Hickson, J., Johnson, A.L.A., Dreyer, W.,  
629 Oschmann, W. 2005. Climate records from a bivalved Methuselah (*Arctica islandica*, Mollusca;  
630 Iceland). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 228, 130-148.
- 631 Schmidt, G. A. 1998. Oxygen-18 variations in a global ocean model, *Geophysical Research Letters*,  
632 25, 1201–1204.
- 633 Schmidt, G.A. 1999. Forward modelling of carbonate proxy data from planktonic foraminifera  
634 using oxygen isotope tracers in a global ocean model, *Paleoceanography*, 14, 482–497.
- 635 Schmidt, G.A., Bigg, G.R., Rohling, E.J. 1999. "Global Seawater Oxygen-18 Database".  
636 <http://data.giss.nasa.gov/o18data/>
- 637 Smellie, J.L., McArthur, J.M., McIntosh, W.C., Esser, R. 2006a. Late Neogene interglacial events  
638 in the James Ross Island region, northern Antarctic Peninsula, dated by Ar/Ar and Sr-isotope  
639 stratigraphy. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 242, 169-187.
- 640 Smellie, J.L., Nelson, A.E., Williams, M. 2006b. Fire and ice: unravelling the climatic and volcanic  
641 history of James Ross Island, Antarctic Peninsula. *Geology Today*, 22, 220-226.
- 642 Smellie, J.L., Johnson, J.S., McIntosh, W.C., Esser, R., Gudmundsson, M.G., Hambrey, M.J., de  
643 Vries, B. Van Wyk. 2008. Six million years of glacial history recorded in the James Ross Island  
644 Volcanic Group, Antarctic Peninsula. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 260,  
645 122-148.
- 646 Smellie, J.L., Haywood, A.M., Hillenbrand, C-D., Lunt, D.L., Valdes, P.J. 2009. Nature of the  
647 Antarctic Peninsula Ice Sheet during the Pliocene: geological evidence and modelling results  
648 compared. *Earth-Science Reviews*, 94, 79-94.
- 649 Whitehouse, M.J., Priddle, J., Symon, C. 1996. Seasonal and annual change in seawater temperature,  
650 salinity, nutrient and chlorophyll a distributions around South Georgia, South Atlantic. *Deep Sea*

- 651        Research Part 1, 43, 425-443.
- 652    Whitehead, J.M., Bohaty, S.M. 2003. Pliocene summer sea surface temperature reconstruction using  
653        silicoflagellates from Southern Ocean ODP Site 1165. *Paleoceanography*, 18, 1075,  
654        doi:10.29/2002PA000829.
- 655    Whitehead, J.M., Wotherspoon, S., Bohaty, S.M. 2005. Minimal Antarctic sea ice during the Pliocene.  
656        *Geology*, 33, 137-140.
- 657    Witbaard, R. 1996. Growth variations in *Arctica islandica* L. (Mollusca): a reflection of hydrography-  
658        related food supply. *ICES Journal of Marine Science*, 53, 981-987
- 659    Williams, M., Smellie, J., Johnson, J., Blake, D. 2006. Late Miocene Asterozoans (Echinodermata)  
660        from the James Ross Island Volcanic Group. *Antarctic Science*, 18, 117–122.
- 661    Williams, M., Haywood, A.M., Harper, E.M., Johnson, A., Knowles, T., Leng, M.J., Lunt, D.,  
662        Okamura, B., Taylor, P., Zalasiewicz, J.A. 2009a. Pliocene climate and seasonality in North  
663        Atlantic shelf seas. *Philosophical Transactions of the Royal Society, London, Series A*, 367, 85-  
664        108 (doi:10.1098/rsta.2008.0224)
- 665    Williams, M., Nelson, A.E., Smellie, J.L., Leng, M.J., Jarram, D.R., Johnson, A.L.A., Haywood,  
666        A.M., Peck, V.L., Zalasiewicz, J.A., Bennett, C.E., Schöne, B.R. 2009b. A high fidelity  
667        molluscan climate record for the Weddell Sea for a warm interval of the Early Pliocene.  
668        Workshop on Pliocene climate, Bordeaux, France, October 22<sup>nd</sup> to 25<sup>th</sup> 2009. Abstract at:  
669        <http://www.plioclimworkshop.com/>

670

671    **Explanation of figures and table**

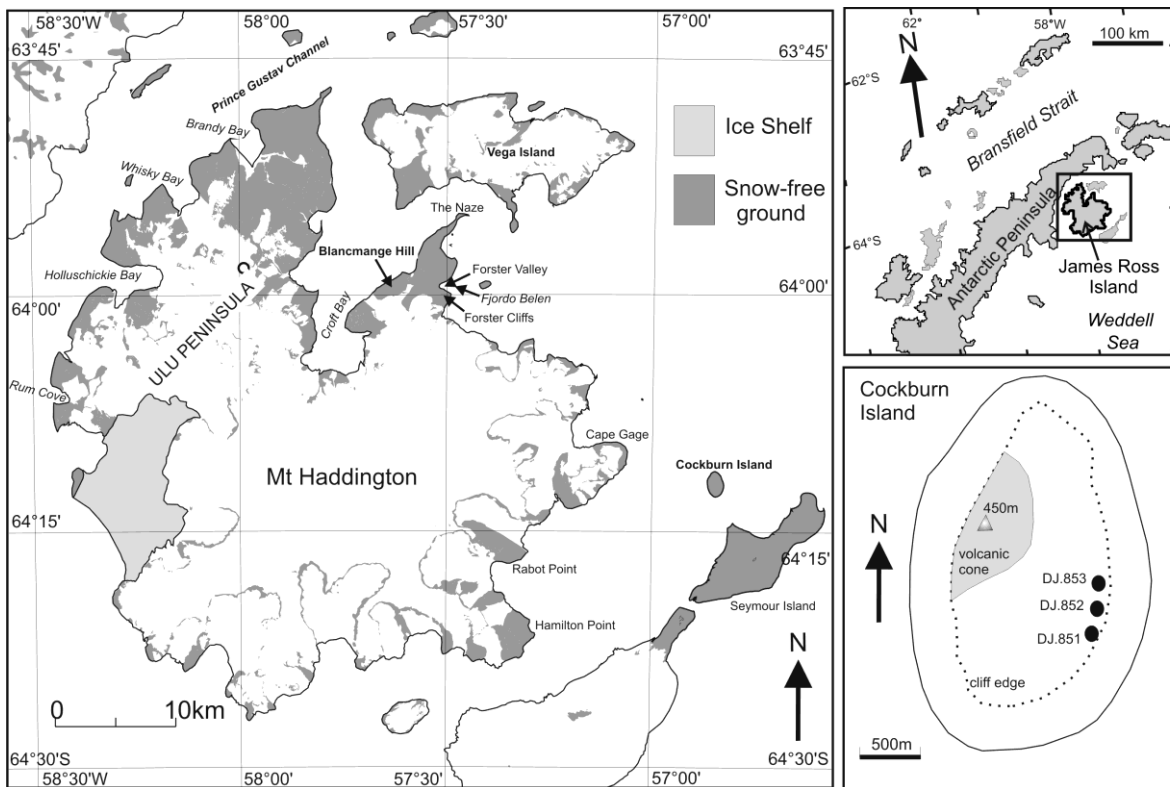


672

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).

682



683

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

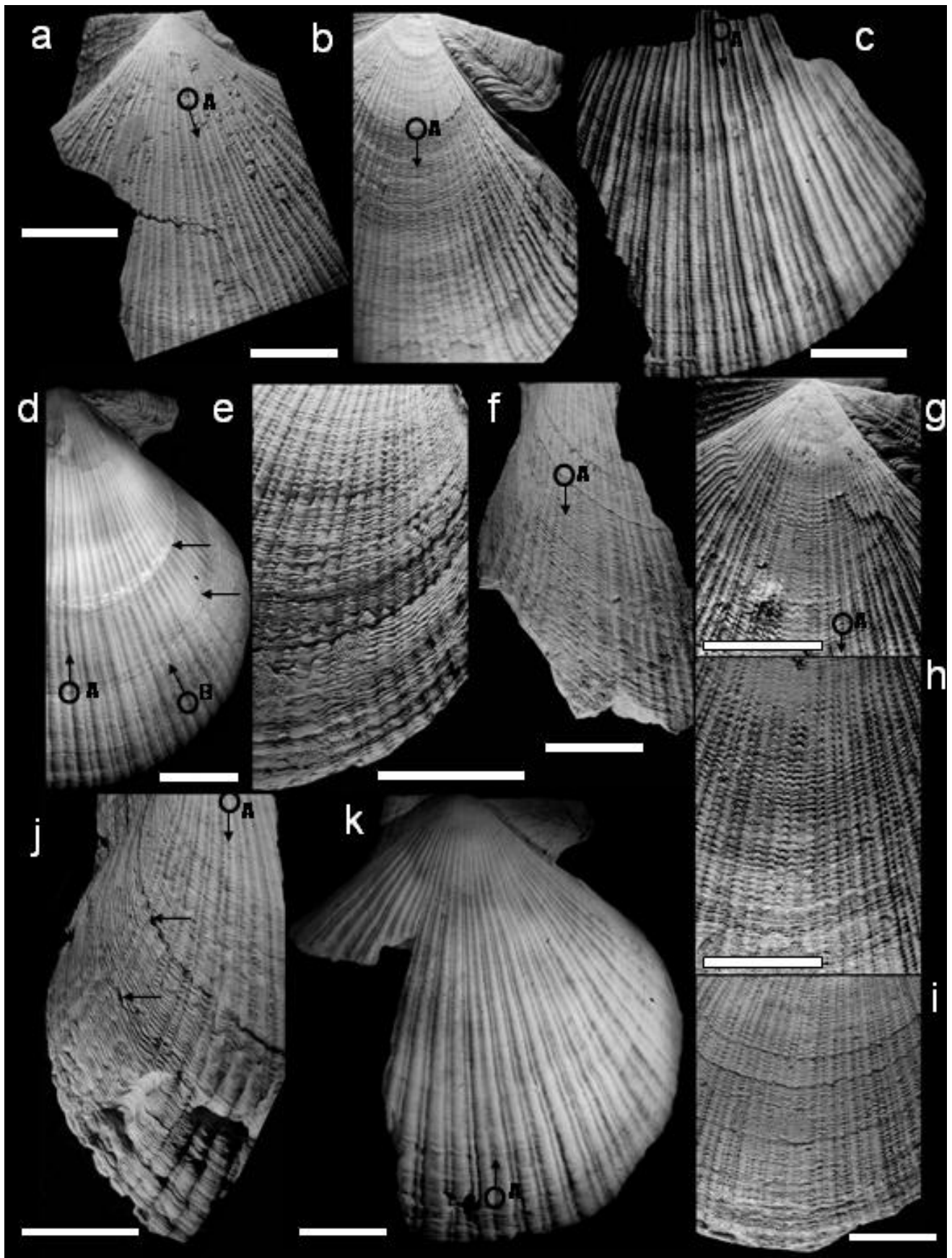
687 morphological analysis mentioned here is sourced from three localities on the east side of Cockburn

688 Island (map bottom right, localities DJ.851, DJ.852 and DJ.853 of H.A. Jonkers 1996, for which see

689 BAS archives). *Austroclamys* material is also widespread in the glacial sediments of James

690 Ross Island, for example at northwest Forster cliffs.

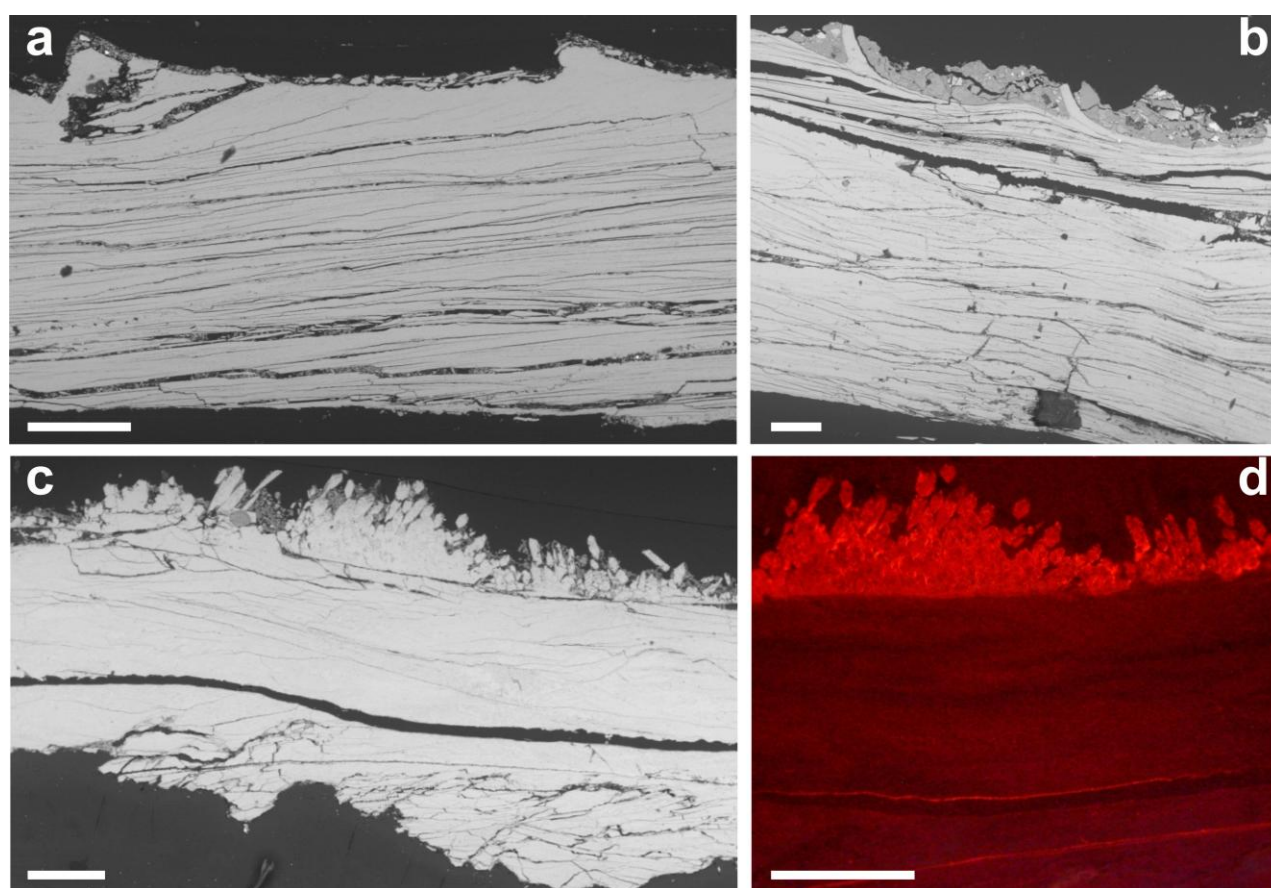
691



692

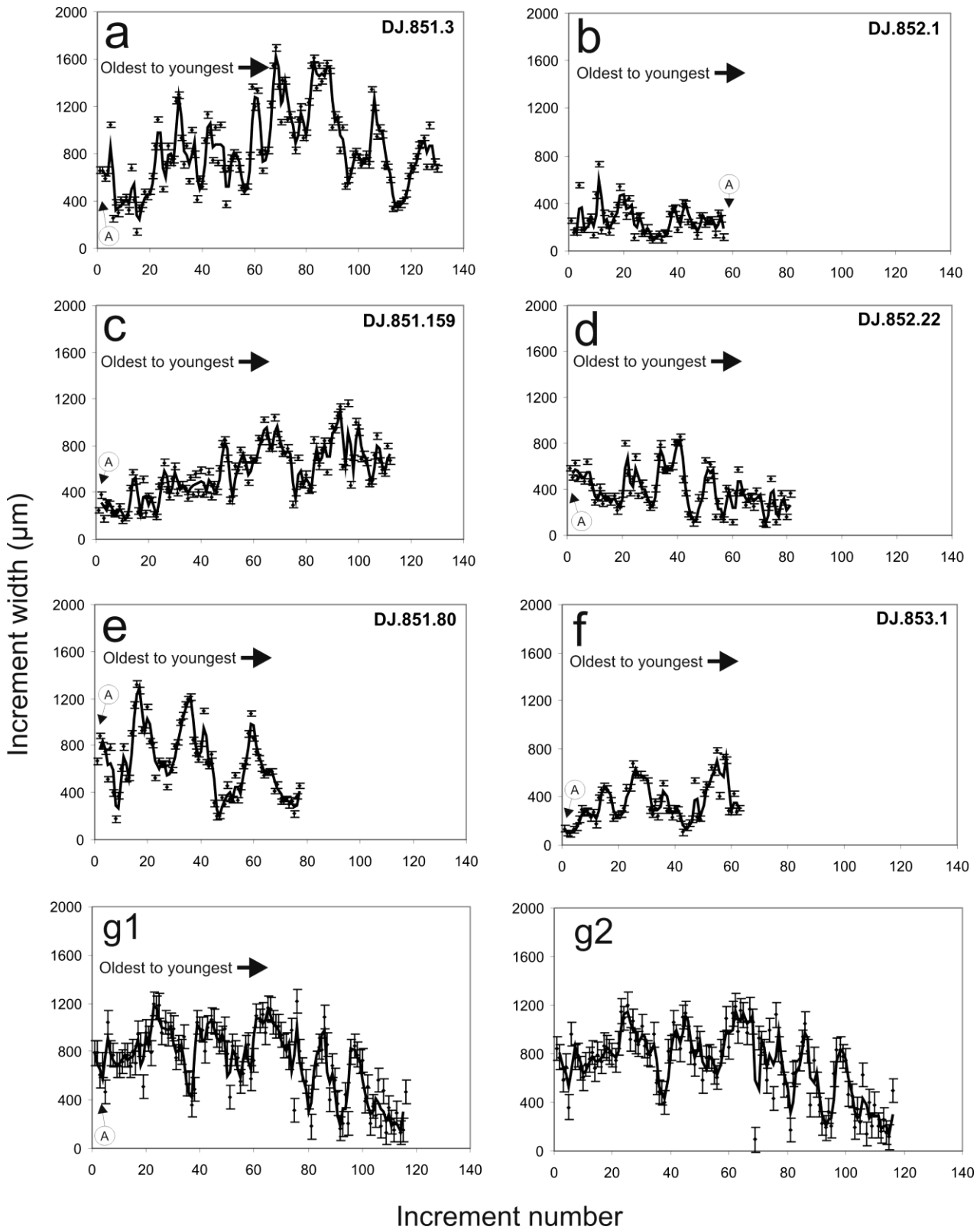
693 **Fig. 3.** Morphology of the bivalve *Austrochlamys*. The images are annotated with open circles  
 694 (labelled 'A' or 'B') to show points on the shell for cross reference with Figures 4 and 6. The arrow

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.

710 The diagenetic cement is brightly luminescent, while the shell foliae are weakly luminescent. Scale  
 711 bars are 0.25 mm.  
 712

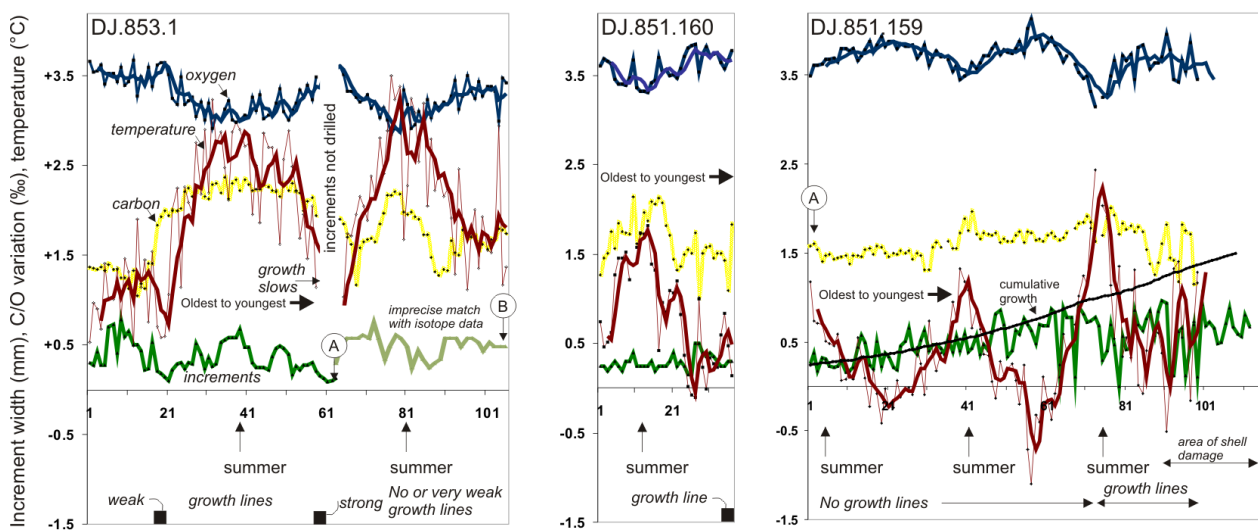


713  
 714 **Fig. 5.** Growth increment analysis of bivalves from the Cockburn Island Formation. Graphs a-f



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  $\mu\text{m}$ , 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  $\delta^{13}\text{C}$  (yellow) and  $\delta^{18}\text{O}$  (blue) as per mil variation (left  
 725 hand vertical scale). Also shown is temperature (red, left hand scale in  $^{\circ}\text{C}$ ) reconstructed using a  
 726  $\delta^{18}\text{O}_{\text{sw}}$  value of  $-0.2\text{‰}$  and the O'Neil et al. (1969) equation [ $T = 16.9 - 4.38(\delta^{18}\text{O}_{\text{c}} - \delta^{18}\text{O}_{\text{sw}}) +$   
 727  $0.10(\delta^{18}\text{O}_{\text{c}} - \delta^{18}\text{O}_{\text{sw}})^2$ ]; 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  $\pm 2$  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 ( $\delta^{18}\text{O}_{\text{sw}}$ of $-0.2\text{‰}$ )	Bivalve DJ.851.159 ( $\delta^{18}\text{O}_{\text{sw}}$ of $-0.2\text{‰}$ ) Craig equation	Bivalve DJ.851.159 ( $\delta^{18}\text{O}_{\text{sw}}$ variable from 0 to $-0.4\text{‰}$ )	Bivalve DJ.851.160 ( $\delta^{18}\text{O}_{\text{sw}}$ of $-0.2\text{‰}$ )	Bivalve DJ.851.160 ( $\delta^{18}\text{O}_{\text{sw}}$ of $-0.2\text{‰}$ ) Craig equation	Bivalve DJ.851.160 ( $\delta^{18}\text{O}_{\text{sw}}$ variable from 0 to $-0.4\text{‰}$ )	Bivalve DJ.853.1 ( $\delta^{18}\text{O}_{\text{sw}}$ of $-0.2\text{‰}$ )	Bivalve DJ.853.1 ( $\delta^{18}\text{O}_{\text{sw}}$ of $-0.2\text{‰}$ ) Craig equation	Bivalve DJ.853.1 ( $\delta^{18}\text{O}_{\text{sw}}$ variable from 0 to $-0.4\text{‰}$ )
-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) [ $T=16-4.14(\delta^{18}\text{O}_{\text{c}} - \delta^{18}\text{O}_{\text{sw}}) + 0.13(\delta^{18}\text{O}_{\text{c}} - \delta^{18}\text{O}_{\text{sw}})^2$ ] and a  $\delta^{18}\text{O}_{\text{sw}}$  value of  $-0.2\text{‰}$ .

745

746 **Appendix 1.** Model calculated values for the  $\delta^{18}\text{O}$  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  $\delta^{18}\text{O}_{\text{sw}}$  [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  $\delta^{18}\text{O}_{\text{sw}}$ .

753

754 Atlantic Calibration:

755

$$756 \delta^{18}\text{O}_{\text{sw}} = 0.24 - 0.008 (P - E) \quad r^2 = 0.7$$

757

758 P - E is given in units of  $\text{cm yr}^{-1}$ .

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  $\delta^{18}\text{O}_{\text{sw}}$  is also dependent upon  
762 mixing because of ocean currents, runoff, etc. The resulting correlation for the Atlantic Ocean  
763  $\delta^{18}\text{O}_{\text{sw}}$  to P - E is reasonable. In addition to P - E we calibrated  $\delta^{18}\text{O}_{\text{sw}}$  against salinity [Levitus and  
764 Boyer, 1994]. This increased the  $r^2$  value to 0.9 for the Atlantic but Haywood et al. (2007)  
765 demonstrated that this did not significantly change the diagnostic predictions of  $\delta^{18}\text{O}_{\text{sw}}$  generated  
766 using P - E for the Pliocene.

767 Nevertheless, it is important to recognise that the use of a salinity:  $\delta^{18}\text{O}$  or P - E:  $\delta^{18}\text{O}$  co-  
768 variation from present-day observations as a diagnostic for the  $\delta^{18}\text{O}$  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  $\delta^{18}\text{O}$  values in the hydrological  
772 cycle [Rohling and Bigg, 1998; Rohling, 2000].

773

774