Late Paleocene Arctic coastal climate inferred from molluscan stable and radiogenic isotope ratios

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Abstract

Characterizing polar climates during past warm intervals is important for understanding ‘greenhouse’ climate dynamics because high-latitude surface temperatures and precipitation patterns are extremely sensitive to global climatic conditions. Model-data comparisons of high-latitude climates during past warm intervals (Cretaceous–Eocene, Pliocene) are currently at odds. Specifically, simulations of past warm climates produce polar regions characterized by sub-freezing temperatures and significant seasonality, whereas limited fossil proxy data indicate higher mean annual temperatures and low seasonality (i.e. an equable climate). We have constructed a data set to infer northern hemisphere polar marine temperatures during the late Paleocene. Seasonal and mean annual temperature and the oxygen isotopic composition of precipitation are reconstructed for an Arctic coastal setting during the Thanetian (57–58 Ma) using fossil shell stable isotope profiles. We estimate that coastal water temperatures varied between 10 and 15°C during the seasons of growth, presumably spring, summer and fall. These findings support paleontological evidence, implying Northern Hemisphere polar climates were seasonally warm during the late Paleocene. In addition, estuarine fossil oxygen isotope profiles show periodic excursions to low values (as low as ~19‰ VPDB), which indicate seasonal pulses of isotopically-depleted freshwater. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Terrestrial and marine geological data indicate that the early Paleogene was the warmest interval of the Cenozoic (Zachos et al., 1994; Greenwood and Wing, 1995). Unfortunately, quantitative paleoclimatic data for this interval are sparse, particularly for the polar regions, and are primarily constrained by planktonic foraminiferal oxygen isotope records from the Southern Ocean (Kennett and Stott, 1990; Zachos et al., 1994). The existence of an early Cenozoic warm and equable Arctic is mainly inferred from Eocene terrestrial faunas and floras from Ellesmere Island, Arctic Canada (Estes and Hutchison, 1980; Axelrod, 1986; Marincovich et al., 1990; Kalugutkar and McIntyre, 1991; Greenwood and Wing, 1995). The only northern high-latitude ocean temperature estimates for the early Paleogene are derived from stable isotope analysis of Paleocene marine bivalves from northern Alaska (Bice et al., 1996) and of Paleocene scaphopods from Ellesmere Island (McKenna, 1980). No open-ocean estimates are known north of ~40°N for the Paleocene. These existing climate proxy data

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are at odds with paleoclimate simulations that imply polar regions were characterized by sub-freezing temperatures and significant seasonality of temperature (Sloan, 1994; Greenwood and Wing, 1995; Sloan and Rea, 1995). The warm and equable terrestrial polar climates that have been inferred from the published high-latitude paleoclimate data set has not been reproduced in any early Cenozoic climate model simulations. Paleoclimate data for the high-latitudes, specifically the Arctic Ocean, are required to constrain and test numerical climate studies.

Under certain conditions, the shell chemistry of fossil mollusks can yield quantitative information about paleoenvironmental conditions (i.e. coastal temperatures). Many mollusks secrete shell material during most of the year in near-isotopic equilibrium with ambient waters (Killingley and Berger, 1979; Arthur et al., 1983; Jones et al., 1989). Consequently, sub-millimeter sampling of shell layers has the potential to resolve seasonal and inter-annual variations in water temperature, salinity, and upwelling (Klein et al., 1996; Andreason and Schmitz, 1998). For paleoclimate studies utilizing fossil shells, tests are required to determine if the primary shell material is pristine. Analysis of shell geochemistry, mineralogy, and microstructures can be used to determine if the original aragonitic shell material (and therefore stable isotope composition) has been preserved (Al-Aasm and Veizer, 1986; Krantz et al., 1996). In short, where the effects of diagenesis on shell chemistry are negligible and salinity effects of runoff can be constrained, the stable isotopic composition of mollusk shells has proven to be a reliable recorder of water temperature (Killingley and Berger, 1979; Bice et al., 1996; Klein et al., 1996; Steuber, 1996; Wilson and Opdyke, 1996).

The purpose of this study is to provide additional constraints on Arctic climate during the late Paleocene using the stable isotope profiles of mollusks from Ellesmere Island, Canada. Specimens of *Dentalium* sp. (infaunal marine scaphopod), *Amauropsis* (marine gastropod), *Arctica ovata* (bivalve), and *Corbícula* sp. (bivalve) have been analyzed, as well as Cretaceous freshwater unionid bivalves (*Unionidae* sp.) from northern Alaska (North Slope). Studies of extant aragonitic scaphopods, gastropods and bivalves indicate that these organisms precipitate shells in oxygen isotopic equilibrium or near-equilibrium with ambient waters (Grossman and Ku, 1986; Weidman et al., 1994; Dettman et al., 1999). Carbon isotopic data for modern *Arctica islandica* suggest that these bivalves form aragonitic shell material that is depleted by $\sim 1\%$ relative to equilibrium values (Weidman, personal communication).

In contrast, the $\delta^{13}C$ values of shells from infaunal organisms (i.e. scaphopods, some gastropods) can be significantly lower than equilibrium marine values due to the incorporation of $^{13}C$-depleted dissolved inorganic carbon (DIC) in porewaters.

Fossil preservation has been determined by mineralogical and geochemical analyses, and specimens ages have been evaluated using the $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ ratios of fossil marine shells. Mean annual temperature (MAT) and seasonality (MART) are reconstructed using the oxygen isotopic composition of marine mollusk shells from a high-latitude coastal site in west-central Ellesmere Island, Canada (Fig. 1). In addition, the oxygen isotopic composition of regional precipitation is estimated from the stable isotope profiles of estuarine mollusks from Ellesmere Island, and compared to data from the North Slope mollusks. These paleoclimate data (coastal MAT, MART, freshwater $\delta^{18}O$) should reflect both open Arctic Ocean conditions and the nearby continental interior characteristics.

### 1.1. Previous work

Only two published marine paleotemperature records exist for the early Cenozoic Arctic Ocean. McKenna (1980) estimated MAT by using stable isotope measurements of aragonitic scaphopods from the Mount Moore Formation on Ellesmere Island. The study by McKenna utilized bulk analyses of marine mollusks, which limits the possibilities for estimating seasonality and other aspects of local climates. This dataset was one part of a study primarily focused on the vertebrates of Ellesmere Island, and deserves to be revisited in more detail. Bice et al. (1996) completed a detailed stable isotope study of calcitic bivalves from the North Slope of Alaska, estimating MAT, MART, and the isotopic composition of precipitation. The isotope profiles of the bivalve *Camptochlamys* (scallop) generated in their study, however, showed evidence of freshwater input, thereby complicating estimates of temperature.
Using a mean shell calcite $\delta^{18}O$ value of $-2.5\%$, they computed mean temperatures of between 11 and 22°C (using seawater $\delta^{18}O$ [VSMOW] values of $-3.8$ and $-1.2\%$, respectively). To reduce uncertainties in their estimates of SST, they used data from freshwater shells and a numerical model to compute local runoff effects on $\delta^{18}O$. This approach, however, required a number of assumptions about the fluvial setting in which the freshwater shells formed, and the paleoenvironmental tolerances of the fossil taxa used in the SST reconstruction.

We have conducted a study similar to that of Bice et al. (1996), constructing detailed stable isotope profiles of fossil mollusk shells with the advantage of analyzing fossils (scaphopods), known to have a purely marine affinity. We also use strontium isotope data to evaluate potential freshwater contribution. Therefore, we are able to estimate water salinity and SST more precisely, which results in greater confidence in our temperature estimates.

1.2. Paleoceanographic and geologic setting

Through most of the Cretaceous, the Arctic Ocean was in open communication with the Pacific Ocean, Gulf of Mexico (Western Interior Seaway), and/or Tethys (Turgai Strait) (Marincovich et al., 1990). By the early Cenozoic, the Arctic Ocean was isolated from the Pacific Ocean and semi-isolated from the Atlantic (Magavern et al., 1996; Marincovich and Gladenkov, 1999). Terrestrial and marine faunal data support the existence of shallow seaways connecting the Arctic to the Atlantic and/or Tethys throughout the Paleocene (Marincovich et al., 1990; Magavern et al., 1996), most likely as a result of sea level high stands.
The upper Paleocene Mount Moore Formation is part of the Cretaceous to Oligocene Eureka Sound Group, a sequence of transgressive-regressive sediments deposited in the eastern Arctic Ocean Basin. Our specimens are from exposures of the Mount Moore Formation on the south side of Strathcona Fiord (modern location: 78.8°N, 81°W; paleo-latitude: 75.3°N), west-central Ellesmere Island (Marincovich and Zinsmeister, 1991). The Mount Moore Formation is comprised primarily of fine-grained, poorly consolidated, quartz-rich, sparsely fossiliferous, shallow marine sandstone (Miall, 1986; Marincovich and Zinsmeister, 1991). These strata are thought to have been deposited during a transgression in a marine embayment located in the northwestern portion of the Remus Basin (Miall, 1986). Sedimentary structures (ripple marks, laminations, low-angle cross-beds, burrows), as well as ostracode, molluscan, and foraminiferal assemblages, imply deposition in a nearshore, shallow to marginal-marine environment, in a mild-temperate marine climate (Marincovich et al., 1990; Marincovich and Zinsmeister, 1991). The presence of scaphopods and inner-sublittoral ostra-codes suggests coastal waters of normal marine salinity (Marincovich et al., 1990). Fossils present in the Mount Moore Formation include open-marine groups (e.g. scaphopods, sharks, Amauropsis) found in thin shale layers, and shallow marine/estuarine molluscan taxa (e.g. Arctica, Corbicula), associated with sandstone layers (Marincovich and Zinsmeister, 1991). Some scaphopod specimens were found in growth positions, while others were lying parallel to bedding but not worn, which suggests minimal post-mortem transport. Arctica ovata shells were found in life position, slightly open but articulated, while both single-valved and articulated specimens of Corbicula were found. There is no evidence of extensive reworking (Marincovich et al., 1990; Marincovich and Zinsmeister, 1991). For more detailed information on the outcrops, see Marincovich and Zinsmeister (1991).

1.3. Age model

Stratigraphic, paleontologic, and paleomagnetic data suggest a late Paleocene age for the Mount Moore Formation. The underlying Mount Lawson Formation has been assigned a Cretaceous through early Paleocene age based on mollusks (Miall, 1986). Terrestrial vertebrates and pollen from the overlying Margaret Formation are correlative with early Eocene (Wasatchian) taxa from North America and Europe, respectively, indicating that the underlying Mount Moore Formation is older than 55 Ma (Miall, 1986). The presence of the marine gastropod Drepanochilus pertetus and the bivalve Cyrtodaria rutupiensis in the MMF, and the absence of characteristic Cretaceous molluscan taxa such as Inoceramus, indicate a Paleocene age (Marincovich and Zinsmeister, 1991). Paleomagnetic data from (lithologically similar beds of Mount Moore Formation outcrops on the north side of Strathcona Fiord) are consistent with deposition during Chron C25-26 (Tauxe and Clark, 1987; Tauxe, personal communication), supporting an age of 59–56 Ma (Berggren et al., 1995 timescale).

2. Methods

Shell mineralogy and microstructure(s) of each mollusk specimen were determined by scanning electron microscopy (SEM), fourier transform infrared analysis (FTIR), and x-ray diffraction analysis (XRD). We analyzed 3–6 samples from each shell by SEM, FTIR, and XRD. Specimens were thin-sectioned (100–200 μm thick), photographed, and visible growth bands digitized (Fig. 2). Carbonate powder was collected from 30 μm-wide grooves milled parallel to growth bands using a Lohmann computerized microsampler (Dettman and Lohmann, 1995). Approximately 30–100 microsamples (~20–40 μg) were collected from each of the eight specimens used for stable isotope analysis. Microsamples from one Arctica and one Dentalium specimen were split for strontium isotope and stable isotope analyses. In addition, one to six bulk samples were collected from thirteen specimens and split for strontium isotope and stable isotope analyses. Powders used in stable isotope analyses were roasted under vacuum at 90°C.

Shell ⁸⁷Sr/⁸⁶Sr ratios were measured on a VG5430-Warp thermal ionization mass spectrometer (TIMS). Carbonate powders were dissolved in 2.5N HCl and a set of ion-exchange columns was used to collect strontium. The strontium fraction was loaded onto a rhenium filament, and then measured on the TIMS. Isotopic ratios are referenced to a NBS-987 standard value of 0.710250 ± 0.000014.
Stable isotope ratios were determined with a Prism gas source mass spectrometer using an ISOCARB automated carbonate system. Samples were reacted with anhydrous phosphoric acid at 90°C. External precision (%RSD) is based on analyses of a lab standard, and is 0.05% for δ^{13}O and 0.08% for δ^{18}O (n = 107). Stable isotope values are reported relative to the VPDB standard using delta notation (δ) as per mil (‰). A standard oxygen isotope–temperature equation derived from aragonitic mollusks was used in this study (Grossman and Ku, 1986):

\[ T = 21.8 - 4.69(\delta^{18}O_{\text{aragonite}} - \delta^{18}O_{\text{water}}) \]

where δ^{18}O_{\text{aragonite}} and δ^{18}O_{\text{water}} are reported relative to V-PDB and VSMOW, respectively.

3. Shell preservation

Our paleoclimatic reconstructions are based solely on analyses of well-preserved fossil specimens. Specific geochemical, mineralogical, and structural criteria (outlined below) were used to assess the degree of preservation for each specimen. Only samples composed entirely of aragonite (as determined by FTIR and XRD analysis) were used in this study. The presence of aragonite generally is indicative of primary carbonate, because it is a relatively unstable phase and will readily convert to calcite during early- and late-stage diagenesis (Al-Aasm and Veizer, 1986). Inspection of fossil and modern aragonitic shells with a petrographic microscope and a SEM revealed that primary shell
microstructures are well preserved and fractures are not present.

Shell geochemistry is also sensitive to diagenesis, and can be used to document minor amounts of aragonite-to-calcite recrystallization (Al-Aasm and Veizer, 1986; Krantz et al., 1996). The presence of significant intra-shell stable isotope variability is consistent with shells having retained their primary geochemical signature. Based on these criteria, we conclude that specimens used in this study have undergone minimal diagenetic alteration.

4. Strontium, oxygen and carbon isotope analyses

The average $^{87}$Sr/$^{86}$Sr ratio of three scaphopod specimens (Table 1), is 0.707800 ± 0.000022 (1σ), identical to late Paleocene open marine values (Howarth and McArthur, 1997). Late Paleocene and Cretaceous bivalves all have higher, more radiogenic strontium isotope values, consistent with growth in $^{87}$Sr-enriched fresh/brackish waters. Mount Moore Formation Paleocene Corbicula specimens ($n = 3$) have an average $^{87}$Sr/$^{86}$Sr ratio of 0.707964 ± 0.000144, and Arctica ovata specimens ($n = 4$) have an average ratio of 0.707917 ± 0.000026. Analyses of three Cretaceous freshwater unionid bivalve specimens (Mount Lawson Formation) yielded an average value of 0.708613 ± 0.000026.

Stable isotope data for all bulk and microsample analyses are presented in Fig. 3. Shell stable isotope profiles for two specimens each of Dentalium and Arctica are shown in Figs. 4 and 5. Mean stable isotope values (based on bulk and microsample analyses) are shown in Table 2. Specimens of Arctica and Corbicula show pronounced (seasonal) variability in $\delta^{13}$C and $\delta^{18}$O, and appear to record three to five years of growth (Fig. 5). In contrast, Dentalium stable isotope profiles do not exhibit large-amplitude oscillations. However, comparison of isotope profiles with shell thin-sections shows a strong correlation between dark (organic-rich?) bands and $\delta^{18}$O minima (Fig. 4). As such, we interpret scaphopod isotope profiles as recording approximately three to six years of growth.

5. Paleoenvironmental analysis

The range of Arctica stable isotope values represents mixing throughout the year of an $^{18}$O and $^{13}$C-enriched marine end-member with an $^{18}$O and $^{13}$C-depleted meteoric water end-member (Fig. 3), which is consistent with growth in an estuarine environment where freshwater input varied throughout the year. In addition, the $^{87}$Sr/$^{86}$Sr ratios of the Mount Moore Formation bivalve specimen are higher than marine

Table 2
Mean stable isotope values and standard deviations for the different mollusks analyzed

<table>
<thead>
<tr>
<th>Locality</th>
<th>Taxa</th>
<th>$\delta^{18}$O (±1σ)</th>
<th>$\delta^{13}$C (±1σ)</th>
<th># of specimens analyzed</th>
<th>Total # analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ellesmere Island</td>
<td>Dentalium</td>
<td>−0.12 ± 0.32‰</td>
<td>2.20 ± 0.17‰</td>
<td>9</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>Amauropis</td>
<td>−0.77 ± 0.47‰</td>
<td>2.27 ± 0.19‰</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Arctica ovata</td>
<td>−7.94 ± 4.87‰</td>
<td>2.40 ± 1.61‰</td>
<td>3</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td>Corbicula</td>
<td>−3.92 ± 0.50‰</td>
<td>3.66 ± 0.74‰</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>North Slope, Alaska</td>
<td>Unionid bivalve</td>
<td>−22.12 ± 0.30‰</td>
<td>0.02 ± 0.11‰</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>
values (0.7078), indicating growth in an environment influenced by $^{87}$Sr-rich river water. Although we do not know the $^{87}$Sr/$^{86}$Sr ratio of Paleocene rivers, it is likely that their drainages were dominated by $^{87}$Sr-enriched rocks (Sloan et al., 1997), similar to Cretaceous (Table 1) and modern Arctic drainages. Furthermore, the association of ripple-marked sandy sediment, vertical ichnofossils, marsh-type flora and coal layers in the Mount Moore Formation with isotopically light, $^{87}$Sr-rich Arctica and Corbicula shells

Fig. 3. Crossplot of microsample and bulk sample oxygen and carbon stable isotope values ($\delta$e, reported relative to VPDB) for late Paleocene mollusks from Mount Moore Formation, Ellesmere Island.

Fig. 4. Oxygen isotope profile of microsampled scaphopod shell with corresponding temperature scale calculated assuming $\delta^{18}$O of seawater is $-2.0\%e$ (using aragonite paleotemperature equation of Grossman and Ku, 1986). Arrows approximate location of thin dark-colored bands in scaphopod cross-section, probably reflecting increased incorporation of organics during the summer months. Sampled region is interpreted to reflect approximately 4–5 yr of shell growth.
is consistent with an estuarine growth environment for these bivalves.

The gastropod and scaphopod oxygen and carbon isotope values average higher than the bivalve values, and show very little intra-shell or inter-specimen variability. The tight clustering of the isotopic values above the inferred mixing line, and the relatively high oxygen isotope values, imply these mollusks lived in marine waters that were not subject to freshwater dilution. This inference is consistent with the observed tolerances of modern scaphopods. These results, in conjunction with published sedimentological and paleontological data (Miall, 1986; Marincovich et al., 1990), suggest that these marine mollusks grew in a shallow coastal setting. In addition, the relatively low $^{87}$Sr/$^{86}$Sr values for the late Paleocene marine fauna from Ellesmere Island support a scenario of open exchange between the Arctic Ocean and other ocean basins at that time. Given the relatively $^{87}$Sr-enriched values of riverine input (as inferred from the bivalve $^{87}$Sr/$^{86}$Sr data), restricted circulation would likely have resulted in higher marine $^{87}$Sr/$^{86}$Sr values than those observed.

6. Further constraints on formation age

When compared with the global marine strontium isotope curve, the scaphopod $^{87}$Sr/$^{86}$Sr values (0.707800) confirm the late Paleocene age assigned to these specimens. An age of 60.2 Ma with uncertainties of $-2.7$ and $+4.0$ myr is calculated from the scaphopod and gastropod strontium isotope data using the LOWESS method (Howarth and McArthur, 1997). In addition, the carbon isotopic composition of the fossil mollusks can be used to further refine the age estimate. Because the offset between shell and water DIC $\delta^{13}$C are known for modern Arctica (and not for living relatives of Dentalium or Amauropsis), we use Arctica shell stable isotope values for this calculation. Assuming Arctica $\delta^{13}$C values are $\sim1\%$ lower than equilibrium aragonite values (e.g. $\sim1\%$ heavier than seawater DIC $\delta^{13}$C), seawater DIC is estimated as between 3.4 and 3.7% (using the highest shell isotope ratios of 4.4 and 4.7%). Based on the global marine carbon isotope record (Zachos et al., 1993), there is only one period during the Cenozoic when DIC $\delta^{13}$C values were this high, at roughly 56–58 Ma. Collectively, the $^{87}$Sr/$^{86}$Sr, $\delta^{13}$C, magnetostratigraphic, and paleontologic data support an age of 57–58 Ma (Thanetian) for these specimens (Berggren et al., 1995 timescale).

7. Paleotemperature reconstruction

Oxygen isotope ratios from scaphopods and gastropods are used to estimate paleotemperatures. Scaphopod oxygen isotope profiles most likely record seasonal temperature changes in coastal waters, and
should therefore exhibit a slightly reduced seasonal amplitude relative to that over the continent. Calculated paleotemperatures are a function of the water δ¹⁸O value used, so any uncertainties in estimating the δ¹⁸O of ambient waters will affect temperature reconstructions. During the late Paleocene the mean δ¹⁸O of seawater is estimated to have been −1.2‰ (VSMOW; Miller et al., 1987). The δ¹⁸O of the modern Arctic Ocean is offset from the (modern) global mean by −0.8‰ (Fairbanks et al., 1992), due to the net transport of ¹⁸O-depleted water from the low to high latitudes by atmospheric processes, and to excess amounts of precipitation relative to evaporation. Model simulations indicate a more intense hydrologic cycle during warm periods (Barron et al., 1989; L. Sloan, personal communication), which would result in greater vapor transport to polar regions. A competing factor is that Rayleigh distillation may have been less extensive at warmer temperatures.

Assuming a minimum Arctic Ocean-global mean δ¹⁸O offset of −0.8‰ (e.g. similar to modern), we compute a mean annual temperature of 12°C and seasonal minimum and maximum temperatures of 10.5 and 15°C, respectively, using an Arctic Ocean δ¹⁸O value of −2.0‰ (Fig. 4). These temperature estimates decrease by 2°C when an Arctic Ocean δ¹⁸O value of −2.5‰ is used. Because of slow winter growth (see below), the mean value of the mollusk shell represents a maximum in terms of mean annual temperature. Due to uncertainties in estimating late Paleocene water δ¹⁸O values, we calculate an error in our paleotemperature reconstruction of ±2°C.

8. Climate equability

Several factors can bias the seasonal temperature variation inferred from intra-shell isotopic analyses. First, sampling of the shell may not have been at close enough intervals to resolve the full amplitude of temperature seasonality. Second, seasonal differences in growth rates can bias paleotemperature reconstructions. Published isotopic data for modern high-latitude mollusks indicate that seasonal variation in growth rates result from changes in food supply, temperature, and reproductive state, with maximum growth during the summer (Barrera and Tevesz, 1990; Barrera et al., 1994; Marshall et al., 1996). The third factor is variations in water δ¹⁸O due to seasonal precipitation and/or runoff may dampen or accentuate seasonal temperature reconstructions.

We have attempted to minimize the first two factors by employing ultra fine-scale microsampling of specimens. The open marine ⁸⁷Sr/⁸⁶Sr and δ¹³C values obtained from scaphopods and gastropods indicate that the third factor had a negligible effect. Nonetheless, these factors limit our ability to fully constrain seasonal variability in temperature. With these caveats, a maximum mean annual temperature of 12°C and a minimum seasonal temperature range of 5°C is calculated using the maximum and minimum oxygen isotope values from the three microsampled scaphopod specimens. This estimate is similar to late Paleocene mean annual temperature and seasonality estimates for northern Alaska (Bice et al., 1996) of 11 and 6°C (seawater δ¹⁸O of −3.8‰; paleo-latitude: 80°N), respectively, and for Seymour Island, Antarctica (Dutton et al., 1998), of 14 and 4°C (seawater δ¹⁸O of −1.2‰; paleo-latitude: 63°S). Furthermore, these coastal temperature reconstructions yield values comparable to existing foraminifer-based Southern Hemisphere high-latitude open-ocean temperature estimates (Kennett and Stott, 1990; Zachos et al., 1994), which indicate that early Paleogene polar temperatures were significantly warmer than at present. Together, the coastal and open-ocean data indicate an asymmetric meridional (pole-to-pole) temperature gradient for the late Paleocene (Fig. 6), with a slope shallower than the modern gradient. This asymmetry likely arose from the different polar distributions of land and sea areas in the two hemispheres. An ice-free Arctic Ocean would represent a large heat sink effectively moderating polar temperatures. In addition, hemispherically asymmetric oceanic heat transport may have also played a role in producing the observed temperature gradient (Bice et al., 2000). If this apparent hemispherically asymmetrical gradient was a robust feature of the late Paleocene, and the Southern Hemisphere high-latitudes were in fact cooler than the Arctic, then it is probable that atmospheric circulation patterns shifted as well. The intertropical convergence zone (ITCZ) and equatorial productivity bands may have been farther north relative to today, if the southern polar regions were cooler than the northern regions.
9. Freshwater endmember

The $\delta^{18}O$ value of regional precipitation and the $\delta^{13}C$ (DIC) composition of fresh water in the Thaneaet can be roughly estimated using bivalve stable isotope data, assuming that the cyclical oscillation in the stable isotopic values mainly reflects seasonal variation in water temperature and isotopic composition. The sharp $\delta^{18}O$ and $\delta^{13}C$ decreases in Arctica shell profiles suggest that runoff was pulsed, recording strongly seasonal (monsoonal-type) $^{18}O$-depleted precipitation (Fig. 5). Assuming that Arctica lived in brackish waters during part of the year and that calcification temperatures were between 0 and 15°C, we calculate freshwater $\delta^{18}O$ value of $-23$ and $-20\%e$ (VSMOW) using the lowest Arctica $\delta^{18}O$ values. Riverine DIC $\delta^{13}C$ is estimated as less than $-3\%e$, assuming a $1\%e$ fractionation between Arctica shell and DIC values. However, it is likely that freshwater end-member stable isotope values were much lower than these. Though no freshwater mollusks occur at this Paleocene locality, our findings are similar to data from Northern Alaskan Thaneaet freshwater bivalves (Bice et al., 1996) that indicate freshwater $\delta^{18}O$ values between $-21$ and $-24.5\%e$ (VSMOW). These values, which are also similar to those of Cretaceous freshwater bivalves from Ellesmere Island (Table 2), suggest that the freshwater endmember for the Paleocene was between $-24$ and $-27\%e$ (VSMOW) for $\delta^{18}O$ and $-1.1\%e$ (VPDB) for $\delta^{13}C$ (DIC).

Low freshwater $\delta^{18}O$ values are consistent with precipitation at low temperatures, extensive distillation via vapor transport/Rayleigh fractionation, and/or convective rain-out effects associated with locally-derived precipitation. In fact, these freshwater $\delta^{18}O$ values are similar to those of modern winter precipitation on the North Slope (mean value is $-24\%e$; Lawrence and White, 1991). Model simulations of early Paleogene climate indicate that this region may have experienced seasonal sub-freezing temperatures and high precipitation (L. Sloan, personal communication). This is in partial conflict with paleobotanical and faunal data which indicate the northern high-latitude coastal regions, at least during the early Eocene, experienced frost-free conditions (Estes and Hutchison, 1980; Axelrod, 1986; Frederiksen, 1993; Greenwood and Wing, 1995; Markwick, 1998), and sedimentologic data suggest very little local relief on Ellesmere Island at that time (Ricketts, 1994; Harrison et al., 1999). The paleontological data also indicate that cold-month mean temperatures were well above freezing ($-5°C$) for coastal and inland areas of Ellesmere Island (Markwick, 1998).

Hemispheric vapor transport-related Rayleigh fractionation could produce isotopically depleted precipitation, assuming that, similar to today: (1) the global mean isotopic ratio of water vapor was in rough
equilibrium with seawater, (2) the primary source of water vapor was the sub-tropics, and (3) the $\delta^{18}O$ of this evaporating water vapor can be approximated using the global mean $\delta^{18}O$ of water vapor (calculated using an air temperature of 25°C, and an ocean $\delta^{18}O$ value of $-1\%$). With these constraints, to create $-20\%$ precipitation in the Arctic, less than 10% of the water vapor originating at low- and mid-latitudes would have to reach the high-latitudes (similar to today, Craig and Gordon, 1965). Alternatively, seasonal precipitation derived from the evaporation of Arctic Ocean water would produce meteoric water $\delta^{18}O$ values greater than $-12\%$ on Ellesmere Island, assuming polar air temperatures of 12°C and an ocean $\delta^{18}O$ value of $-2.0\%$. Locally-derived precipitation could be further depleted to achieve $-20\%$ $\delta^{18}O$ values via Rayleigh distillation if 85–90% of the vapor had been rained out during transport. We conclude that low freshwater $\delta^{18}O$ values resulted from hemispheric vapor transport-related Rayleigh fractionation, potentially modified further by locally-derived convective precipitation. This is supported by paleontological data, which indicate regionally humid and warm conditions at that time (e.g. Kalugutkar and McIntyre, 1991). We cannot exclude the possibility of seasonally cooler temperatures (near freezing), although this scenario appears less plausible.

10. Conclusions and implications

Stable isotopic data from fossil mollusk shells are used to reconstruct the paleoclimate setting for a coastal region of the Arctic Ocean during the late Paleocene. Surface temperature records for this important interval are exceedingly sparse and, in many cases, of ambiguous quality. The strontium isotope, carbon isotope, paleomagnetic, and paleontologic data constrain the age of the upper part of the Mount Moore Formation to 57–58 Ma (Thanetian). Marine scaphopod and gastropod oxygen isotope data indicate a mean annual coastal water temperature of 12 ± 2°C, with a minimum seasonality of 5°C, and maximum summer temperatures of 15 ± 2°C. In addition, the isotopic composition of estuarine bivalves indicates an $\delta^{18}O$ value of $-20$ to $-22\%$ for regional precipitation, which is consistent with strongly seasonal, $^{18}O$-depleted precipitation. The low-oxygen isotope values for freshwater suggest either seasonally cooler temperatures and/or, more likely, significant transport-related distillation.

When our coastal SST data are combined with published cold month mean temperature estimates of $\sim 5°C$ from Ellesmere Island for a similar time interval (early Eocene; Estes and Hutchison, 1980), we calculate a MART of 10°C. This suggests that warm, equable (high MAT; low MART) climates existed in coastal high-latitude settings, but not nearly as warm as those inferred by an earlier study of brackish water mollusks (Bice et al., 1996). These paleotemperature data support paleobotanical-based climate reconstructions that imply the Arctic was characterized by a relatively warm, humid, temperate climate with relatively mild summers and winters in the late Paleocene. Additional data from terrestrial sequences and/or shallow-marine mollusks from Russia could be used to verify this.

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