HIGH-RESOLUTION STABLE ISOTOPE PROFILES OF A DIMITOBELID BELEMNITE: IMPLICATIONS FOR PALEODEPTH HABITAT AND LATE MAASTRICHTIAN CLIMATE SEASONALITY

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ABSTRACT

Oxygen and carbon isotope ratios were measured on belemnites, planktonic foraminifera, and benthic foraminifera collected from Late Cretaceous sediments on Seymour Island, Antarctic Peninsula, to compare the relative depth habitats of these organisms and to provide insight on temperature seasonality at high southern latitudes near the end of the Cretaceous. Average $\delta^{18}O$ and $\delta^{13}C$ values of the belemnite Dimitobelus seymouriensis overlap with those of benthic foraminifera; these values are significantly different ($p < 0.01$) from isotopic compositions recorded by planktonic foraminifera. This comparison shows that D. seymouriensis likely inhabited waters below the surface summer mixed layer of the outer shelf. These results suggest that average $\delta^{18}O$ of D. seymouriensis is a good indicator of intermediate-to-deep-shelf water conditions, which in this locality is a good approximation for pelagic water temperatures in the Southern Ocean. Measurements of $\delta^{18}O$ on high-resolution samples across belemnite growth bands indicate that annual temperature variability of sub-mixed-layer neritic water along the Antarctic coastline was 5°C on average with a mean annual temperature of 6°C.

INTRODUCTION

Stable isotopes and belemnites have been intimately linked since the dawn of stable isotope geochemistry, when a Cretaceous belemnite from the Pee Dee Formation in South Carolina was adopted as an isotopic standard (Craig, 1957). Although belemnites have historical prominence in the field of stable isotope geochemistry, the interpretation of belemnite stable isotope compositions is still debated. For example, disparity between cool paleotemperatures derived from belemnites and comparatively warm paleotemperatures recorded by planktonic foraminifera at high southern latitudes during the Cretaceous sparked a discussion of the suitability of belemnite oxygen isotope values ($\delta^{18}O$) as a proxy for surface-water temperature (Huber et al., 1995; Huber and Hodell, 1996; Price et al., 1996). The interpretation of belemnite $\delta^{18}O$ ultimately hinges upon whether the habitat of belemnites was in warmer surface waters or in cooler, deeper-water environments. In this study, the paleodepth habitat of a late Maastrichtian dimitobelid belemnite species is investigated by comparing the stable isotope composition of belemnites and planktonic- and benthic-dwelling foraminifera. High-resolution sampling is employed for the belemnites to determine geochemical variability within growth bands. Seasonal stable isotope profiles help to elucidate both the paleodepth habitat and seasonal variability of neritic water temperatures at high latitudes during the Late Cretaceous.

Belemnites are extinct coleoid cephalopods that had a soft-tissue outer body and secreted an internal carbonate rostrum or guard. Rare soft-tissue molds of belemnites display a body form similar to that of modern squids. Consequently, inferences regarding belemnite ecology and life history are frequently drawn from modern squid (Stevens and Clayton, 1971; Doyle and MacDonald, 1993). Unfortunately, squids demonstrate a variety of behaviors, making it difficult to generalize belemnite paleoecology. Pelagic squids (Oegopsida) inhabit the open ocean but spend part of their life cycle inshore, while neritic squids (Myopsida) dwell in the shallower waters on the inner shelf (Clarke, 1966). Some neritic squids migrate inshore to spawn, while some pelagic squid migrate inshore immediately prior to spawning on the continental slope (Clarke, 1966). Migratory behavior associated with spawning is particularly noteworthy because recent coleoids exhibit mass mortality immediately after spawning (Mangold, 1987). Hence, the distribution of fossil belemnite guards may not necessarily be representative of their preferred habitat during the majority of their lifespan. Nonetheless, the prevalent association of fossil belemnite guards with shallow marine deposits (Stevens, 1965) has contributed to the notion that belemnites were restricted to shallow shelf habitats.

Operating under the assumption that belemnites inhabited surface waters, many early stable isotope studies invoked belemnite $\delta^{18}O$ values to infer sea-surface temperatures for ancient climates (e.g., Lowenstam and Epstein, 1954; Longinelli, 1969). More recently, several researchers proposed that belemnites may have lived in deeper waters and therefore that belemnite $\delta^{18}O$ values underestimate the temperature of surface waters (Anderson et al., 1994; Price and Sellwood, 1994; van de Schootbrugge et al., 2000). Uncertainty as to the depth of belemnite guard calcification persists in part because these organisms were nektonic and therefore had the potential to migrate either laterally or vertically in the water column during their life cycles.

Belemnites migrated laterally within distinct biogeographic provinces during the Mesozoic (Doyle, 1987b). Belemnites initially developed a widespread distribution in the Early Jurassic and formed distinct Boreal and Tethyan realms in the Middle Jurassic (Doyle, 1987b; Doyle and Pirrie, 1999). The appearance of a definable Austral fauna in the Early Cretaceous (Valanginian–Aptian) was followed by the demise of the Tethyan fauna in the Cenomanian (Doyle and Howlett, 1989; Doyle and Pirrie, 1999). This bipolar pattern of Boreal and Austral faunas persisted until the disappearance of belemnites in the late Maastrichtian (Doyle et al., 1994).

We investigate the paleodepth habitat and the potential for migratory behavior for the belemnite Dimitobelus seymouriensis by comparing stable isotope data ($\delta^{18}O$ and $\delta^{13}C$) of D. seymouriensis with those of planktonic and benthic foraminifera collected from the López de Bertodano Formation on Seymour Island, Antarctic Peninsula. This section is unique in that it contains well-preserved belemnites as well as benthic and planktonic foraminifera, allowing comparison of $\delta^{18}O$ and $\delta^{13}C$ of belemnites to those of organisms inhabiting surface and deep shelf waters. These data taken together also provide insight into the dynamics of high-latitude climate seasonality at the end of the Cretaceous.

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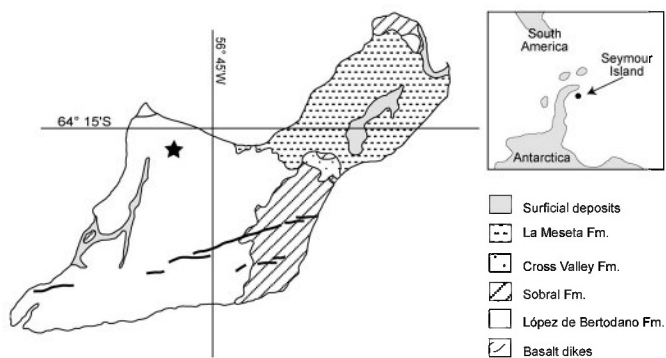
FIGURE 1—Geologic map of Seymour Island, Antarctica. Inset shows location of Seymour Island, ~100 km offshore of the Antarctic Peninsula. The López de Bertodano Formation (Late Cretaceous) crops out on the southern portion of the island. Star = approximate location of the belemnite locality.

GEOLOGIC SETTING

Seymour Island is located in the James Ross Basin on the northeast tip of the Antarctic Peninsula at latitude 64°16'S and longitude 56°45'W (Fig. 1). Late Cretaceous paleogeographic reconstructions (e.g., Lawver and Dalziel, 1992; Hay et al., 1999) indicate that this island has been situated near the Antarctic Circle since the Early Cretaceous. The island contains diverse and well-preserved Maastrichtian–Paleogene terrestrial and marine fossil assemblages that weather out from gently dipping shallow marine sediments. Absence of vegetation and permanent ice cover affords nearly continuous outcrop exposure on most of the island.

The López de Bertodano Formation on Seymour Island comprises 1,190 m of predominantly unconsolidated, clay-rich, sandy siltstone with occasional interbeds of fine calcareous sandstone that ranges in age from Maastrichtian through Paleocene. The depositional environment of this sequence has been interpreted as an open marine shelf, below effective wave base but above the shelf-slope break, based in part upon the high abundance of silt and clay and notable absence of sedimentary structures (Macellari, 1988). The presence of articulated bivalves in their life position indicates a relatively low energy depositional environment (Macellari, 1988), and the occurrence of rugoglobigerinid planktonic foraminifera in this sedimentary succession further supports the interpretation of an environment deeper than inner shelf (Sliter, 1972; Douglas and Savin, 1975; Caron and Homewood, 1983). The unconsolidated nature of these sediments, good-to-excellent fossil preservation, and low vitrinite reflectance values (Palamarczuk et al., 1984) indicate that the López de Bertodano Formation was never deeply buried.

BELEMNITE AND FORAMINIFERAL DISTRIBUTIONS

Dimitobelus seymouriensis is known only from sample locality 768 of Doyle and Zinsmeister (1988), ~575 m below the Cretaceous-Tertiary (K-T) boundary on Seymour Island (Zinsmeister, 2001). This horizon has an estimated age of 68.2 Ma based on Sr-isotope stratigraphy of McArthur et al. (1998). Members of the family Dimitobelidae (Aptian–Maastrichtian) are restricted to regions poleward of 30° S Cretaceous paleolatitude (Doyle, 1987a; Doyle and Zinsmeister, 1988). In the Antarctic Peninsula region, Dimitobelidae are known from coarse-grained sediment in the Alexander Island fore-arc basin, the coarse-grained volcaniclastic sediments of the Gustav Group in the Lower Cretaceous back-arc basin, and in fine-grained, shelfal marine sediments of the Marambio Group, which includes the López de Bertodano Formation (Doyle and Howlett, 1989). Dimitobelids are also common in shallow-water environments with coarse sediment in New Zealand (Stevens, 1965).

Dimitobelus seymouriensis specimens from Seymour Island were collected from a poorly consolidated, medium-brown, fossiliferous, sandy siltstone that is exposed along a discontinuous low cliff in the southwest portion of the island (Fig. 1). Associated fauna include serpulid worms

(*Rotularia*), large spatulate echinoid spines (*Cyathocidaris*), rare crinoid ossicles, and rare corals (Doyle and Zinsmeister, 1988) but do not include abundant bivalve macrofossils that exist up section (Zinsmeister and Macellari, 1988).

The foraminiferal taxonomy and biostratigraphy of the López de Bertodano Formation has been documented by Huber (1988). Nearly all samples from this sequence yield low-diversity, agglutinated benthic foraminifera but some also contain diverse, well-preserved calcareous benthic species and rare, low-diversity planktonic species. Barrera et al. (1987) obtained oxygen and carbon isotope data from some of the samples yielding calcareous foraminifera, but these isotopic data have insufficient stratigraphic coverage for the purposes of the present study.

METHODS

Foraminifera analyzed for stable isotopes were selected from samples 28d and 165 of Huber (1988) because they are correlative to within ~50 and 40 m, respectively, below the belemnite bed and yield a sufficient abundance of calcareous benthic and planktonic foraminifera. Calcareous foraminifera have not been recovered from sediments that are stratigraphically closer to the belemnite bed. Values for $\delta^{13}C$ and $\delta^{18}O$ were measured on single-taxon separates, including one upper-mixed-layer planktonic species (*Rugoglobigerina rugosa*) and four benthic species (*Alabamina creta, Anomalinoides piripaua, Cibicides seymouriensis*, and *Gyroidinoides nitidus*).

High-resolution samples were collected from four specimens of *D. seymouriensis* by drilling consecutive paths spaced at ~50 μm parallel to the growth bands on a cleaned and polished longitudinal section. The apical line, apex, and outer surfaces were avoided during sampling. These powdered carbonate samples were subsequently split for stable isotope ($\delta^{13}C$ and $\delta^{18}O$) and elemental (Ca, Mg, Sr, Fe, and Mn) analysis (Figs. 2, 3; see Supplementary Data[1]). Stable isotope analyses were conducted using an automated Kiel device directly coupled to a Finnigan MAT 251 isotope-ratio mass spectrometer and are reported relative to the Vienna Pee Dee Belemnite standard ($1\sigma < 0.1\%$). Several individual foraminifera were combined for each stable isotope measurement. Elemental analyses were carried out on a Finnigan Element inductively coupled plasma mass spectrometer (relative standard deviation $<2\%$) at a fixed Ca concentration of 800 ppb to avoid complications associated with Ca-matrix effects (e.g., Rosenthal et al., 1999). After samples were dissolved in nitric acid, aliquots were taken to measure the calcium concentration using a Perkin-Elmer inductively coupled plasma optical emission spectrometer and samples were diluted accordingly for subsequent analysis by inductively coupled plasma mass spectrometry. Paleotemperatures are calculated assuming a seawater $\delta^{18}O$ value of -0.98% for an ice-free world, and temperatures are derived using the equation of Kim and O'Neil (1997; α = fractionation factor, cc = calcite, T = temperature in Kelvin [K]):

$$1000 \ln \alpha \ (cc - H_2O) = 18.03(10^3 \cdot T^{-1}) - 32.42.$$

This equation was chosen because it is calibrated down to lower temperatures in the range of those recorded by the late Maastrichtian fossils we examined. Applying a correction of -0.23% to account for high-latitude surface-water salinity according to the equation reported in Zachos et al. (1994) would shift temperatures by approximately $-1°C$ relative to those reported here.

RESULTS

Foraminferal Preservation

Barrera et al. (1987) observed excellent preservation of foraminiferal calcite for specimens from Seymour Island with scanning electron microscope images of wall microtextures and by comparison of interspecific

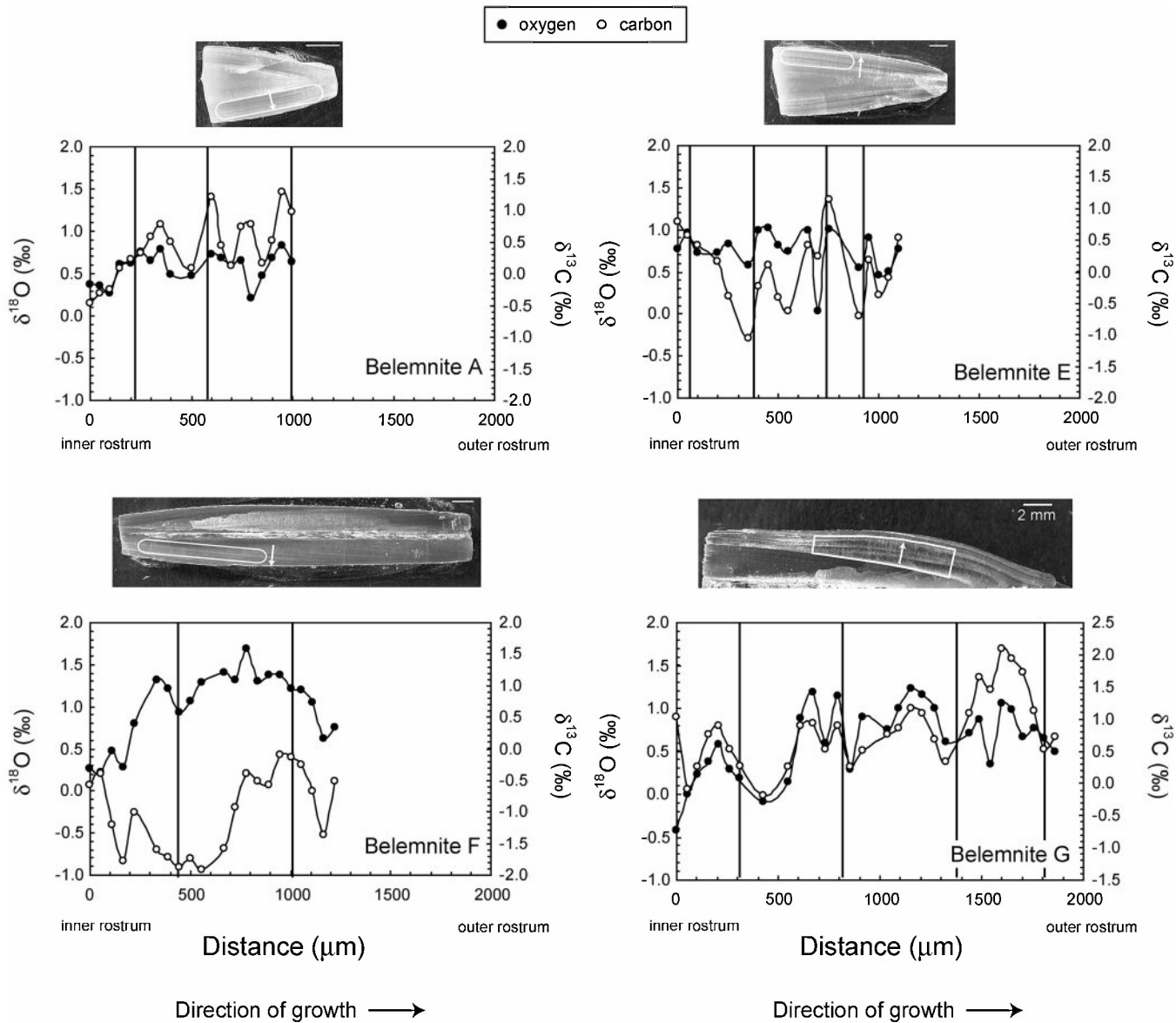---

[1] www.paleo.ku.edu/palaios

FIGURE 2—High-resolution stable isotope data for four belemnite specimens, López de Bertodano Formation. Samples drilled parallel to growth bands (= black vertical lines); solid circles = δ^{18}O, open circles = δ^{13}C. Diagenetic samples (see Fig. 3) not included in this diagram. White outlines on images of cross sections = area sampled. All scale bars = 2 mm.

isotope differences for the benthic taxa. Further scanning electron microscope analyses were not conducted for this study, but all species except *Anomalinoides piripaua* exhibit the same glassy wall texture and were collected within several meters stratigraphically of the well-preserved foraminifera examined by Barrera et al. (1987). The *A. piripaua* specimens had a sugary texture that was visible under light microscope, which may be the result of shell recrystallization or minor secondary calcite overgrowth. Higher porosity of the shell wall in *A. piripaua* may account for this greater diagenetic susceptibility relative to the other taxa.

Stable isotope results confirmed the suspicion that at least one of the *A. piripaua* samples (from sampling locality 165) contained secondary calcite, as both δ^{18}O and δ^{13}C values are significantly more negative than those of the other benthic taxa (Fig. 4). The other *A. piripaua* sample has stable isotope compositions that are consistent with those of the other benthics. Based on these results, only one of the *A. piripaua* samples is considered to be altered with respect to its geochemistry. The remaining benthic δ^{18}O values from Seymour Island cluster near the δ^{18}O value of coeval benthic foraminifera from Maud Rise (Ocean Drilling Program (ODP) Site 690; Barrera and Huber, 1990), which is a deeper-water (pe-

lagic) site ~700 km north of the Antarctic coastline at the same latitudinal position as Seymour Island. The similarity of benthic δ^{18}O compositions at these two sites with different diagenetic and burial histories provides external confirmation that benthic δ^{18}O compositions recorded at Seymour Island for this study are primary and reflect regional conditions, with the exception of the aforementioned *A. piripaua* sample.

Although the texture of planktic *R. rugosa* specimens from Seymour Island does not display obvious diagenetic artifacts, one of the *R. rugosa* samples (also from locality 165) is considerably more negative with respect to the δ^{18}O and δ^{13}C values of other planktic samples from Seymour Island and Maud Rise (Fig. 4). Interestingly, the oxygen isotope composition of the altered *R. rugosa* sample is very similar to the altered *A. piripaua* sample and to yet another *A. piripaua* sample from the same sampling locality (165) reported by Barrera et al. (1987). This convergence of δ^{18}O values is characteristic of meteoric diagenesis and defines a meteoric waterline (Fig. 4; see Lohmann, 1987). During meteoric diagenesis, marine carbonates typically experience alteration in δ^{18}O until equilibrium is attained with the diagenetic fluid, which is graphically represented by samples that plot along the meteoric waterline. Carbon
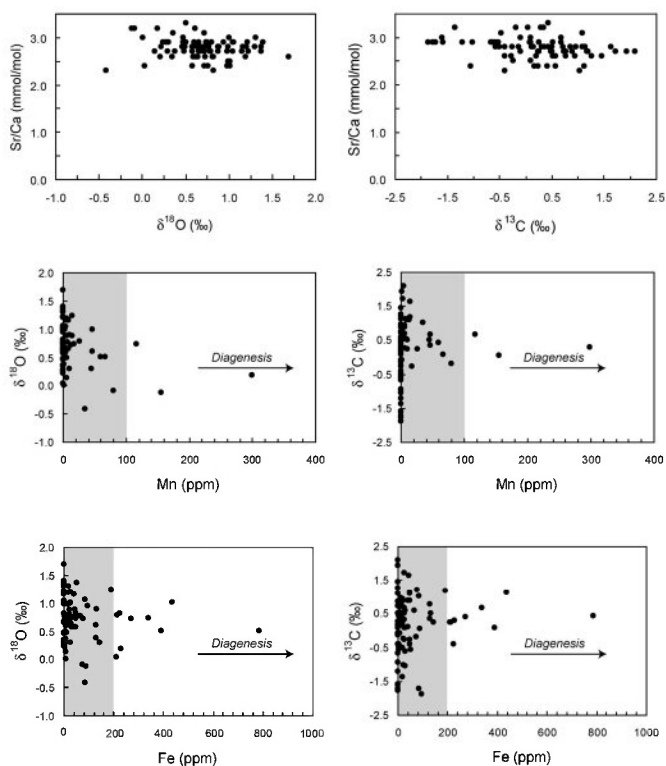
FIGURE 3—Trace and minor element compositions (Sr/Ca, Fe, Mn) plotted vs. stable isotope compositions ($\delta^{18}O$, $\delta^{13}C$) to evaluate diagenesis. Sr/Ca values are relatively high and do not show positive correlation with $\delta^{18}O$, indicating retention of primary geochemistry. Fe and Mn concentrations in belemnite calcite are elevated for a subset of samples, but these samples do not correspond to extreme values of stable isotope compositions. Gray-shaded area = trace element concentrations consistent with unaltered biogenic calcite. Data falling outside this zone have been excluded from the remaining analysis and discussion.

FIGURE 4—Stable isotope evaluation of diagenesis. $\delta^{18}O$ and $\delta^{13}C$ cross plot defines fields of primary compositions for surface and benthic dwellers. Meteoric waterline denotes oxygen isotope equilibration with diagenetic fluids and is characterized by lower $\delta^{18}O$ values. Subsequent depletion in ^{13}C moves samples down along the meteoric waterline as the carbon equilibrates. Two samples analyzed in this study and one reported by Barrera et al. (1987), both from locality 165, display evidence for diagenetic alteration of stable isotope compositions. $\delta^{18}O$ data for benthic foraminifera plotted using interspecific offsets reported in Barrera et al. (1987). SI = Seymour Island; MR = Maud Rise. *R. rugosa* = *Rugoglobigerina rugosa*; *A. piripaua* = *Anomalinoides piripaua*.

isotope equilibration requires more time because there is much less carbon than oxygen in the diagenetic fluid. In this case, altered samples also display some depletion of ^{13}C. Because alteration follows this classic inverted-J path on a plot of $\delta^{13}C$ versus $\delta^{18}O$, we can use this graphical representation to distinguish primary and altered samples.

Belemnite Preservation

Belemnite calcite in the Seymour Island specimens is a translucent, yellow-to-light-brown color with concentric banding. Growth lines in belemnite guards are thought to represent alternating organic-rich and organic-poor zones of calcite (Sælen, 1989; Podlaha et al., 1998) that correspond to laminae obscurae and laminae pellucidae, respectively (Müller-Stoll, 1936). These growth bands are thought to be secreted on a quasi-annual timescale. The calcite constituting the relatively organic-rich laminae obscurae is more porous and therefore more susceptible to diagenetic alteration than laminae pellucidae. High-resolution sampling was employed to characterize chemical composition and degree of preservation across both zones of calcite.

Specimens of *D. seymouriensis* display variation in their stable isotope composition through time (Fig. 2). Seasonal fluctuation in $\delta^{18}O$ has been reported for other belemnite specimens (Urey et al., 1951; Longinelli, 1969; Spaeth et al., 1971), yet the range of variability was found to be more pronounced in specimens with evidence of recrystallization (Longinelli, 1969; Veizer and Fritz, 1976). Podlaha et al. (1998) noted the association of more negative values of $\delta^{18}O$ and elevated Fe and Mn contents in cathodoluminescent secondary calcite filling the laminae obscurae. These observations led to the conclusion that $\delta^{18}O$ variation across growth bands in belemnites may be a diagenetic artifact rather than a primary signal reflecting temperature variation.
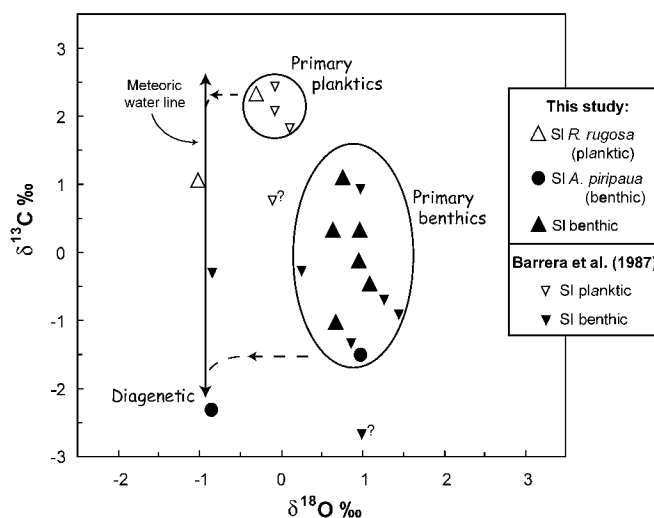
Belemnite specimens were screened for diagenesis using (1) trace element composition, (2) degree of covariation between elemental and isotopic data, (3) cathodoluminescence, and (4) comparison of stable isotope values in belemnites to other faunal elements and diagenetic carbonate in Upper Cretaceous sediment of the James Ross Basin. Measured Fe and Mn concentrations and Sr/Ca ratios fall largely within established thresholds for pristine biogenic calcite and are not indicative of diagenesis (Morrison and Brand, 1987; see Fig. 3). Two samples exhibit elevated Fe or Mn concentrations (Fe > 500 ppm or Mn > 200 ppm); these samples were excluded from further analysis. *Dimitobelus seymouriensis* specimens collected from Seymour Island do not display a correlation between elevated trace element and stable isotope composition. When viewed under a cathodoluminoscope, the cement of the sedimentary host rock appears bright orange, indicating the presence of Mn-rich fluids during lithification. In contrast, belemnite specimens from Seymour Island are nonluminescent. Though lack of luminescence does not completely rule out diagenesis, in this case it attests that the belemnite specimens were not altered by pore waters that were present during lithification. The similarity of stable isotope compositions of these belemnites to those of other faunal elements in similar environments nearby with different burial and diagenetic histories (see the Results and Discussion sections below) provides further independent evidence that the primary geochemical signals have been preserved. As none of the aforementioned screening procedures reveal positive indicators for diagenesis of the belemnite calcite, these specimens are considered to have retained their primary geochemistry.

Stable Isotope Data

Ontogenetic patterns of $\delta^{18}O$ and $\delta^{13}C$ generally parallel each other across several bands in each of four *D. seymouriensis* specimens (Fig. 2). A Pearson's correlation coefficient for these two variables is significant ($p < 0.01$) in only two of the specimens (Belemnite A and G) and is not significant for the stable isotope data of all four belemnite specimens combined. Temporal variation in $\delta^{18}O$ and $\delta^{13}C$ is interpreted as a primary signal in the absence of compelling evidence for diagenesis.

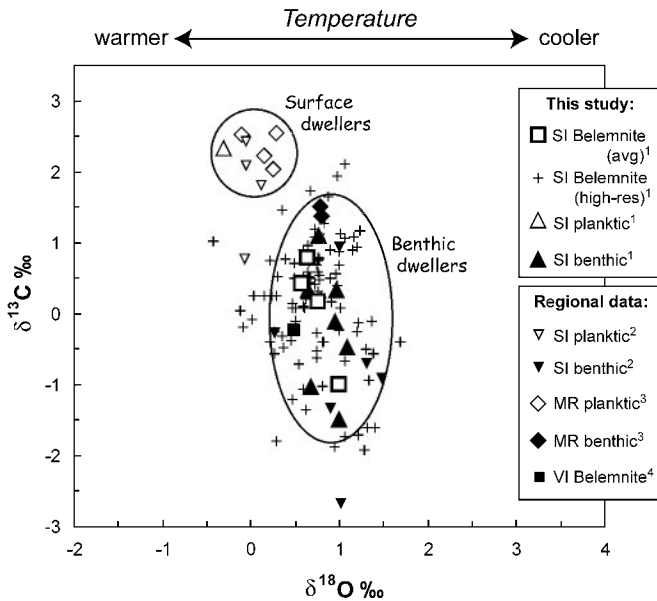Stable isotope values ($\delta^{18}O$ and $\delta^{13}C$) recorded by the belemnite *D.*

FIGURE 5—$\delta^{18}O$ and $\delta^{13}C$ cross plot of all well-preserved specimens. Stable isotope compositions for planktonic and benthic foraminifera shown with average compositions of belemnites and individual, high-resolution belemnite samples. Fields of planktic and benthic compositions drawn in same positions as Fig. 4. Note overlap of belemnite and benthic foraminifera $\delta^{18}O$ and $\delta^{13}C$ values, indicating similar depth habitats. SI = Seymour Island; MR = Maud Rise; VI = Vega Island. Data sources: [1]this study, [2]Barrera et al. (1987), [3]Barrera and Huber (1990), [4]Pirrie and Marshall (1990).

seymouriensis fall within the field of values observed for benthic foraminifera, which is distinct from the stable isotope composition of planktonic foraminifera (Fig. 5). Average $\delta^{18}O$ values of the belemnites range from $+0.6\%$ to $+1.0\%$, $\delta^{18}O$ of benthic foraminifera span from $+0.4\%$ to $+1.1\%$, and planktonic foraminifera yield a $\delta^{18}O$ value of -0.3%. Foraminiferal stable isotope compositions are similar to the range reported for Seymour Island specimens at nearby sampling localities (Barrera et al., 1987). High-resolution samples drilled from the belemnites range in $\delta^{18}O$ values from -0.4% to $+1.7\%$ and scatter around benthic foraminifera data on a $\delta^{13}C$ versus $\delta^{18}O$ plot. Despite the isotopic variability observed within each belemnite specimen, average $\delta^{18}O$ and $\delta^{13}C$ of all belemnites are near those of benthic foraminifera. Using a Student's t-test, we find that the population mean $\delta^{18}O$ of belemnites is indistinguishable from that of benthic foraminifera and is significantly higher than that of planktonic foraminifera ($p < 0.01$). This statistical result holds true with respect to the population of foraminifera analyzed in this study and also for the combined population of foraminifera examined in this study and from Sites 165, 28a, and 28d in Barrera et al. (1987). Carbon isotope compositions are also distinctly different for planktonic foraminifera relative to those of belemnites and benthic foraminifera, which have similar $\delta^{13}C$ values. This observation is also statistically robust according to the Student's t-test method.

Belemnite $\delta^{18}O$ and $\delta^{13}C$ values from Seymour Island are similar to those reported for another species of *Dimitobelus* collected from late Maastrichtian sediments on Vega Island, located $\sim$40 km from Seymour Island (Pirrie and Marshall, 1990; see Fig. 4). Though the precise age of the specimen from Vega Island relative to *D. seymouriensis* specimens from Seymour Island is uncertain, agreement in isotopic composition between these species provides independent confirmation of belemnite stable isotope values recorded at Seymour Island.

DISCUSSION

Paleodepth Habitat of *Dimitobelus seymouriensis*

Carbonate secreted in relatively warm surface ocean waters has lower $\delta^{18}O$ values than carbonate secreted in cooler water at depth owing to

the temperature-dependent fractionation of oxygen isotopes. Conversely, carbonate secreted in equilibrium with surface waters usually has a higher $\delta^{13}C$ value than the carbonate formed at depth because of primary productivity in surface waters, which draws down ^{12}C relative to ^{13}C (Kroopnick et al., 1977). These expected stable isotope–water depth trends are observed for planktonic and benthic foraminifera from Seymour Island (Fig. 5).

Average values of belemnite stable isotope compositions are consistent with the relatively cool, deep-water conditions recorded by the benthic foraminifera. Despite the range of variability exhibited by the high-resolution samples, it is apparent that belemnite $\delta^{18}O$ does not record surface-mixed-layer temperatures, as represented by the isotopic composition of planktonic foraminifera from Seymour Island. It is assumed here that foraminiferal $\delta^{18}O$ is precipitated in equilibrium with ambient seawater. Metabolic effects on $\delta^{18}O$ fractionation in planktonic foraminifera can be a few tenths of a per mil in magnitude, but even this would not be enough to bring planktonic foraminifera values fully into the field of average belemnite compositions. This comparison suggests that average values of belemnite $\delta^{18}O$ and $\delta^{13}C$ are an appropriate proxy for benthic water conditions in this open-shelf environment rather than for surface-water conditions as recorded by the planktonic foraminifera. Inferences for belemnite depth habitat based on this result include at least two possibilities: (1) belemnites calcify their rostra in equilibrium with intermediate-to-deep shelf water; or (2) belemnites calcify their rostra in surface waters, but have a vital effect offset. The latter option is considered unlikely given that modern mollusks precipitate their shells in equilibrium with ambient seawater with respect to oxygen isotopes (Epstein et al., 1953), the vital effect offset would have to be quite large, and the vital effect would have to offset both $\delta^{18}O$ and $\delta^{13}C$ to coincidentally encompass the range of both $\delta^{18}O$ and $\delta^{13}C$ of benthic foraminifera (Fig. 5). To more rigorously test between these two alternatives and ascertain if belemnites have a consistent offset from surface waters due to a vital effect, similar comparisons are needed at other localities, particularly at different latitudes, where the vertical thermal gradient in the water column may have been different.

Because the foraminifera were collected slightly below the belemnites in the stratigraphic section, a third option must be entertained: that belemnites lived and secreted their calcitic guards in equilibrium with surface waters but that temperature or seawater $\delta^{18}O$, or both, changed significantly during the intervening period. The sedimentation rate in this section is estimated at $\sim$175 m per million years using an age model based on Sr-isotope stratigraphy (Howarth and McArthur, 1997; McArthur et al., 1998; Zinsmeister, 2001; see Fig. 6). The magnitude of this rate is consistent with independently calculated sedimentation rates based upon radiometric glauconite dates (Macellari, 1984) and biostratigraphy (Askin, 1988). Therefore, this hypothesis would therefore require an extremely rapid 5°C cooling of surface waters within $\sim$230 kyr during the late Maastrichtian. Such an abrupt cooling episode would have had a significant impact on high-southern latitude biota, but this possibility is unlikely given the absence of evidence (isotopic or otherwise) for such an event coincident with the belemnite horizon (68.2 Ma). In fact, the $\delta^{18}O$ record from Seymour Island is quite stable through this portion of the section (Barrera et al., 1987). Hence, the more parsimonious conclusion is that stable isotope compositions of belemnites match those of benthic foraminifera because they calcify in equilibrium with water below the surface mixed layer.

This analysis of stable isotope compositions demonstrates that average belemnite stable isotope compositions do not agree with those of surface-dwelling planktonic foraminifera and suggests a nektobenthic habitat for *D. seymouriensis*. These results are consistent with several other studies that report belemnite stable isotope compositions enriched in ^{18}O or depleted in ^{13}C, or both, relative to (presumed) surface dwelling organisms and epifaunal, shallow-water taxa (Tan et al., 1970; Anderson et al., 1994; Price and Sellwood, 1994; van de Schootbrugge et al., 2000; Table 1). Comparisons between stable isotope compositions of co-occurring am-
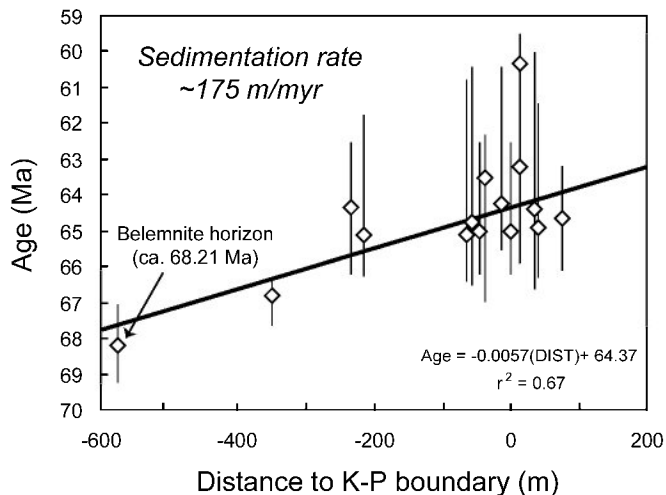
FIGURE 6—Average sedimentation rate of the López de Bertodano Formation, calculated using previously reported Sr-isotope data (McArthur et al., 1998), assigned to stratigraphic levels according to the plane-projection method (Zinsmeister, 2001). Age estimates assigned for each Sr-isotope measurement follow methods of Howarth and McArthur (1997). One anomalously high $^{87}Sr/^{86}Sr$ value at the Cretaceous-Tertiary (K-T) boundary was excluded from the regression. Error bars indicate the combined uncertainty of the analytical technique and the 95% confidence interval associated with the secular $^{87}Sr/^{86}Sr$ curve for seawater (Howarth and McArthur, 1997).

monites and belemnites suggest that ammonites were living in warmer (i.e., shallower) water with higher productivity (Tan et al., 1970; Anderson et al., 1994; Ditchfield et al., 1994). There are inconsistencies in comparative studies with benthonic organisms such as bivalves and brachiopods; in some cases, belemnites display overlapping stable isotope compositions, and, in other instances, they reflect even deeper water conditions in comparison to these bottom dwellers (Lowenstam and Epstein, 1954; Anderson et al., 1994). This discrepancy could be attributed to vertical or lateral migration of belemnites or different water depths of epifaunal, benthic taxa in these two studies relative to the depth habitat of the belemnites.

High-Resolution Geochemical Profiles

The stable isotope profiles of *D. seymouriensis* are not purely sinusoidal in shape, as one might expect for seasonal-scale data. Because belemnites are nekton and can migrate both vertically and laterally in the water column, they are capable of sampling a variety of environmental conditions, which become overprinted upon seasonal cycles of temperature and productivity. In accordance with the stable isotope–water depth trends described earlier, vertical migration should manifest as negative covariation of belemnite $\delta^{18}O$ and $\delta^{13}C$. In contrast, *D. seymouriensis* records ontogenetic stable isotope patterns that are generally positively correlated (Fig. 2). Interpretation of this observation is complicated by

uncertainties in the relationship between molluscan $\delta^{13}C$ and the carbon isotope composition of dissolved inorganic carbon in seawater. Molluscan carbonate $\delta^{13}C$ can be offset from isotopic equilibrium with ambient water because of variable incorporation of metabolic carbon (Tanaka et al., 1986; Krantz et al., 1987). In this case, because belemnite $\delta^{13}C$ exhibits the same range recorded by the benthic foraminifera, it is likely that both organisms are precipitating shells near equilibrium with respect to carbon isotopes. Therefore, positive covariation in the high-resolution stable isotope data more likely represents seasonal changes in temperature, primary productivity, or salinity possibly superimposed with some lateral migration, but it does not appear to be consistent with vertical migration.

High-resolution Mg/Ca and Sr/Ca data do not show statistically significant correlation with either $\delta^{18}O$ or $\delta^{13}C$ for the data set as a whole or for within each individual specimen (cross plots not figured). In particular, the lack of correlation between Mg and $\delta^{18}O$ within each specimen is contrary to negative correlations observed for bulk data collected over a stratigraphic succession for some belemnite genera, which have been interpreted to indicate that Mg/Ca is an effective paleothermometer in belemnites (McArthur et al., 2000; Bailey et al., 2003; McArthur et al., 2004; van de Schootbrugge et al., 2005). Because our data do not display a robust correlation between Mg/Ca and $\delta^{18}O$, we feel that interpretation of temperature on the basis of Mg/Ca compositions of these belemnites is still premature.

Late Cretaceous Paleoclimate and Seasonality

The absolute magnitude of seasonal variability in $\delta^{18}O$ data derived from calcareous taxa in shallow marine environments is dictated to varying degrees by temperature, salinity (e.g., Klein et al., 1996), growth rates of shell secretion (e.g., Goodwin et al., 2003), and sampling density (e.g., Patterson, 1998). In an intermediate-to-deep shelf habitat, seasonal contributions of fresh-water runoff should be of minimal influence to the $\delta^{18}O$ profiles. The magnitude of seasonal fluctuations in growth rate of belemnite guards is unknown, but it is plausible that the belemnites slowed or ceased growth in winter because of restricted light and, hence, nutrient availability at high southern latitudes that would have biased average $\delta^{18}O$ values toward warmer temperatures. The number of samples per growth band varies depending on the total band thickness and ranges from 5 to 11 samples per band, capturing seasonal to monthly resolution variability. High-resolution sampling was conducted at the highest spatial resolution possible ($\sim$50 μm) and should be considered a minimum estimate of seasonal temperature ranges.

If variation in $\delta^{18}O$ is interpreted solely in terms of temperature, this indicates that *D. seymouriensis* lived in waters ranging from 4°C to 10°C (excluding one outlier on either side of the range recorded). This magnitude of temperature variation is reasonable for a benthic, outer-shelf habitat and is similar to annual temperature ranges recorded by late Maastrichtian bivalves recovered from outer-shelf sediments up section (Dutton, 2003). Dicot wood anatomy of Maastrichtian fossil wood from the Antarctic Peninsula also suggests a magnitude of temperature seasonality

TABLE 1—Comparison between belemnite stable isotope ($\delta^{18}O$ and $\delta^{13}C$) compositions and other co-occurring taxa. Belemnites generally record cooler temperatures and are depleted in ^{13}C relative to shallow-dwelling taxa. †Oxygen isotope data converted to paleotemperatures assuming $\delta^{18}O_{SEAWATER} = -0.98\%$ Vienna Standard Mean Ocean Water, using equations of Kim and O'Neil (1997) for calcite taxa and Grossman and Ku (1986) for aragonite taxa.

| Organism	Belemnite T(°C)† (relative to organism in column 1)	Belemnite $\delta^{13}C$ (relative to column 1)	Source
Bulk rock (coccoliths)	4–13 °C colder	more negative	van de Schootbrugge et al., 2000
Ammonites	6 °C colder	$\sim -1\%$	Anderson et al., 1994
Bivalves	similar (1–2 °C colder)	similar	Anderson et al., 1994
Ammonites	2.5 °C colder	-1.3%	Ditchfield et al., 1994
Ammonites	11 °C colder	-1%	Tan et al., 1970
Brachiopods	colder	N/A	Lowenstam and Epstein, 1954
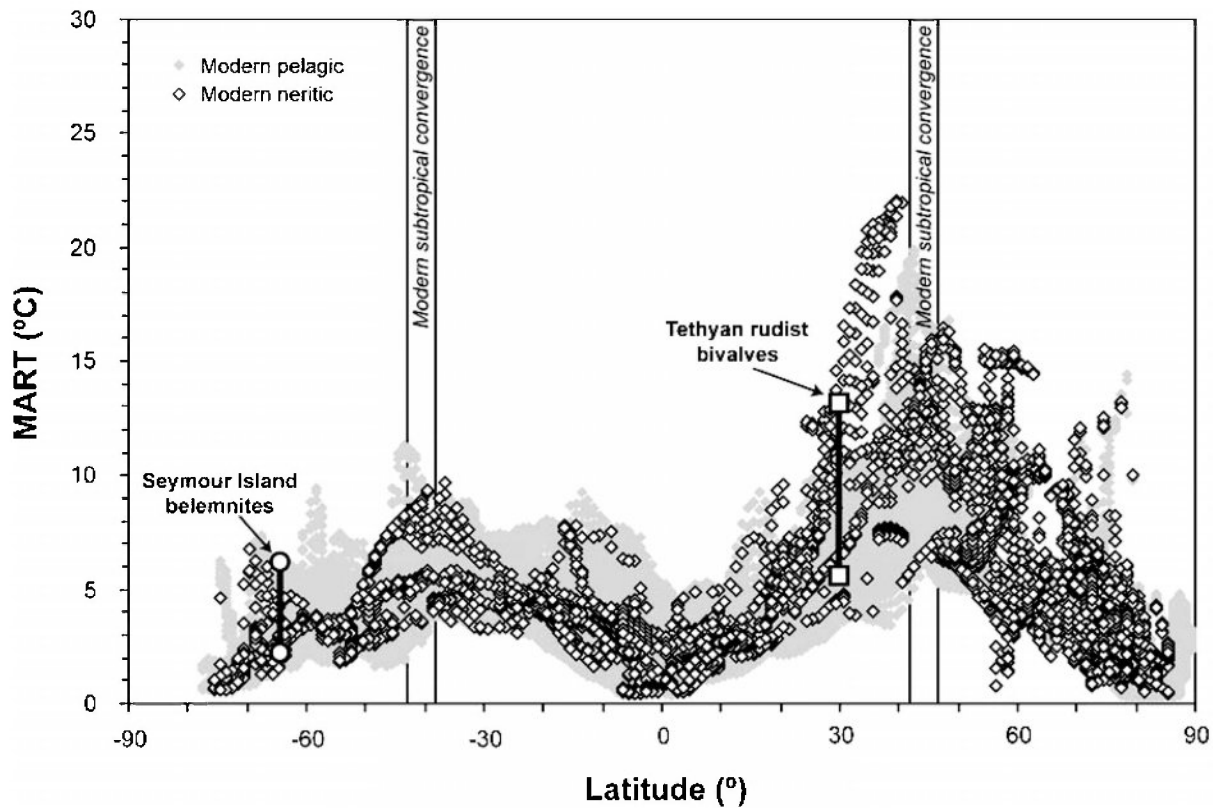
FIGURE 7—Mean annual range in surface ocean temperature (MART) vs. latitude. Modern temperature ranges (Levitus and Boyer, 1994) calculated from mean monthly temperature data to make them comparable to fossil archives sampled at approximately monthly resolution. Belemnite (this study) and fossil rudist (Steuber, 1996, 1999; Immenhauser et al., 2005) data display MART indistinguishable from modern data at similar latitudes. Belemnite $\delta^{18}O$ likely underestimates temperature ranges experienced in shelfal surface waters because these belemnites lived in intermediate to deep outer shelf water.

similar to that recorded by the Seymour Island belemnites (Francis and Poole, 2002).

Assuming that belemnite calcite was secreted yearlong, average values of the high-resolution samples should represent mean annual temperatures of intermediate-to-deep-shelf waters along the Antarctic coastline. *Dimitobelus seymouriensis* specimens from Seymour Island record a mean annual temperature of 6 °C, whereas the mean-annual-temperature estimate derived from the Maastrichtian-age paleoflora on the Antarctic Peninsula is 7.3 °C (Francis and Poole, 2002). In summary, the belemnite $\delta^{18}O$ data corroborate the presence of a cool-temperate climate at southern high latitudes where near-surface-water temperatures reach minima above freezing.

There are few other records of intra-annual-scale Late Cretaceous climate in the shallow marine realm. This paucity of seasonal-scale data relates in part to the sparseness of well-preserved biotic carbonate. Although most fossil rudist bivalve reefs have experienced pervasive calcite remineralization of their aragonite inner shells, the thin veneer of low-Mg calcite on the outside of these shells is more resistant to alteration and provides one of the few sources of shallow marine seasonality data for the Late Cretaceous (Steuber, 1996, 1999; Immenhauser et al., 2005). Late Cretaceous belemnite and rudist bivalve seasonality are compared to modern latitudinal patterns of surface ocean temperature seasonality in Figure 7 to better understand the relation between mean annual temperature and mean annual range of temperature during globally warm climates characterized by relatively shallow latitudinal mean-annual-temperature gradients. Modern mean annual range of temperature has been computed based on monthly averages (equivalent to 12 samples per year) to approximate the sampling resolution of fossil archives.

Despite a warmer global climate in the Late Cretaceous than in the present, at a first glance existing seasonality data for the Late Cretaceous appear to display the same range of values as modern neritic environ-

ments at equivalent latitudes (Fig. 7). This is not to say that sea-surface temperature seasonality at Seymour Island today is the same as it was in the Late Cretaceous. In fact, modern sea-surface temperature seasonality along the eastern margin of the Antarctic Peninsula is 2.5°C (Levitus and Boyer, 1994), whereas the Maastrichtian belemnite data record at least 6°C of seasonality. Also, the amplitude of the mean annual range of temperature for *D. seymouriensis* would be dampened in deep shelf water relative to surface conditions, so these data probably underestimate actual seasonality. Hence, the belemnite data actually suggest a larger sea-surface seasonality signal than modern observations, which would be expected for an ice-free Late Cretaceous world.

It is also worth noting that planktonic foraminiferal $\delta^{18}O$ from Seymour Island is slightly lower than age-equivalent planktonic foraminiferal $\delta^{18}O$ from Maud Rise (Barrera and Huber, 1990), which is a deeper-water (pelagic) site ~700 km north of the Antarctic continent at the same latitudinal position as Seymour Island (Fig. 5). Surface water closer to the coastline may be a few degrees warmer or less saline; both of these effects would produce lower $\delta^{18}O$ values for neritic planktonic foraminifera. Average belemnite values, however, are closely approximated by benthic foraminifera from Maud Rise (paleodepth = ~1500 m).

CONCLUSIONS

Comparison with planktonic and benthic foraminifera suggests that *Dimitobelus seymouriensis* was nektobenthonic, inhabiting intermediate-to-benthic water depths of the outer shelf. This interpretation is consistent with findings that belemnites record cooler paleotemperatures than some shallow-water taxa. Although *D. seymouriensis* appears to live in intermediate-to-deep shelf waters, this does not imply that all belemnites exhibited similar behavior. Different species or genera of belemnites may well have occupied a wide range of niches corresponding to variable

paleodepth habitats. Combination of belemnite $\delta^{18}O$ data with $\delta^{18}O$ data of planktonic foraminifera should be made with caution, and comparative stable isotope studies of belemnites with other taxa should be incorporated when possible to assess the significance of belemnite-derived paleotemperatures.

These data indicate that by ~68.2 Ma a cool-temperate climate had replaced the more tropical climate of the mid-Cretaceous at high southern latitudes (e.g., Huber, 1998). Although the modern mean annual range of temperature for sea-surface waters adjacent to Seymour Island is only 2.5 °C, and these belemnites record up to 6°C of annual variability, temperature seasonality recorded by *D. seymouriensis* at Seymour Island and by Tethyan rudist bivalves in the Late Cretaceous is not significantly different from modern latitude-equivalent data.

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