Deep-sea paleotemperature record of extreme warmth during the Cretaceous

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ABSTRACT

Oxygen isotope analyses of well-preserved foraminifera from Blake Nose (30°N paleolatitude, North Atlantic) and globally distributed deep-sea sites provide a long-term paleotemperature record for the late Albian–Maastrichtian interval that is difficult to reconcile with the existence of significant Cretaceous ice sheets. Given reasonable assumptions about the isotopic composition of Cretaceous seawater, our results suggest that middle bathyal water temperatures at Blake Nose increased from ~12 °C in the late Albian through middle Cenomanian to a maximum of 20 °C during the latest Cenomanian and earliest Turonian. Bottom waters were again ~12 °C during the middle Campanian and cooled to a minimum of 9 °C during the Maastrichtian. Correlative middle bathyal foraminifera from other ocean basins yield paleotemperature estimates that are very similar to those from Blake Nose. Comparison of global bottom-water temperatures and latitudinal thermal gradients suggests that global climate changed from a warm greenhouse state during the late Albian through late Cenomanian to a hot greenhouse phase during the latest Cenomanian through early Campanian, then to cool greenhouse conditions during the mid-Campanian through Maastrichtian.

Keywords: Cretaceous climate, greenhouse effect, oxygen isotopes, ocean circulation, polar regions.

INTRODUCTION

Greenhouse conditions prevailed during the Cretaceous. Isotopic data, paleobiogeography of terrestrial and marine organisms, leaf physiognomy, and distribution of climatically sensitive sediments indicate temperatures generally warmer than present, especially at high latitudes (e.g., Barron, 1983; Herman and Spicer, 1997; Frakes, 1999). Despite evidence for warmth, conditions at high latitudes have been debated. Continental ice sheets in Antarctica have been invoked to explain short-term global eustatic sea-level fluctuations during the Cretaceous (Matthews and Poore, 1980; Abreu et al., 1998) and the occurrence of glendonites and diamictites in Lower Cretaceous sediments deposited at high paleolatitudes (Kemper, 1986; Frakes et al., 1992). Moreover, oxygen isotope data from belemnites and other macroinvertebrates could indicate at least seasonally cold temperatures and limited polar ice caps (Sellwood et al., 1994; Ditchfield et al., 1994). Evidence for warmth and lack of any unequivocal Cretaceous glacial deposits convinced most workers that the Cretaceous was effectively ice free, but recent studies have revived the glacial hypothesis as an explanation for high-frequency sea-level changes and have cited strontium (Stoll and Schrag, 1996) and oxygen isotopic data (Miller et al., 1999; Stoll and Schrag, 1996, 2000) as evidence. Resolution of the Cretaceous ice-sheet debate requires new oxygen isotope data that can be reliably used for Cretaceous paleotemperature reconstructions.

To that end we have generated $\delta^{18}O$ data from monospecific samples of benthic foraminifera and two to three species of planktic foraminifera for the late Albian–Maastrichtian (ca. 101–65 Ma) using samples from Ocean Drilling Program (ODP) Sites 1049 and 1050 (Fig. 1). We compare these data with composite foraminiferal $\delta^{18}O$ records from southern high-latitude deep-sea sites to test whether they reveal similar long-term climate trends. We also combine new $\delta^{18}O$ data from additional deep-sea sites with previously published $\delta^{18}O$ data to reconstruct latitudinal surface- and bottom-water temperature gradients for 1–2 m.y. time slices within the late Albian, Cenomanian-Turonian boundary interval, mid-Campanian, and mid-Maastrichtian. Our results indicate that greenhouse conditions prevailed throughout the late Albian–Maastrichtian, and bottom-water and high-latitude temperatures were too warm to be consistent with significant ice buildup at polar latitudes.

MATERIAL AND METHODS

Sediments cored at Blake Nose Sites 1050 and 1049 were deposited at ~1200 and 1500 m water depths, respectively, and are composed of clay- and organic carbon–rich sediments alternating with chalky marls in the upper Albian, and of foraminiferal-nannofossil chalk in the Cenomanian-Maastrichtian interval (Norris et al., 1998). The sequence at Site 1050 is complete from the upper Albian through uppermost Cenomanian, but an ~0.5 m.y. hiatus occurs across the Cenomanian-Turonian boundary (Huber et al., 1999), and multiple hiatuses occur within the Turonian-Maastrichtian interval (Fig. 2). The sequence at Site 1049 includes mid-Campanian and Maastrichtian pelagic chalk separated by an ~5 m.y. unconformity.

Stable isotopic analyses were obtained from single taxon separates of one or two epifaunal benthic foraminiferal species and two to three

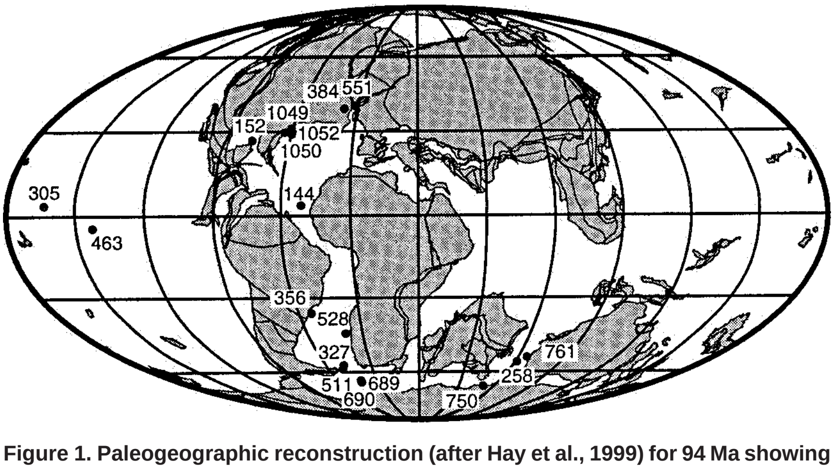

Figure 1. Paleogeographic reconstruction (after Hay et al., 1999) for 94 Ma showing locations of sites discussed in this study.

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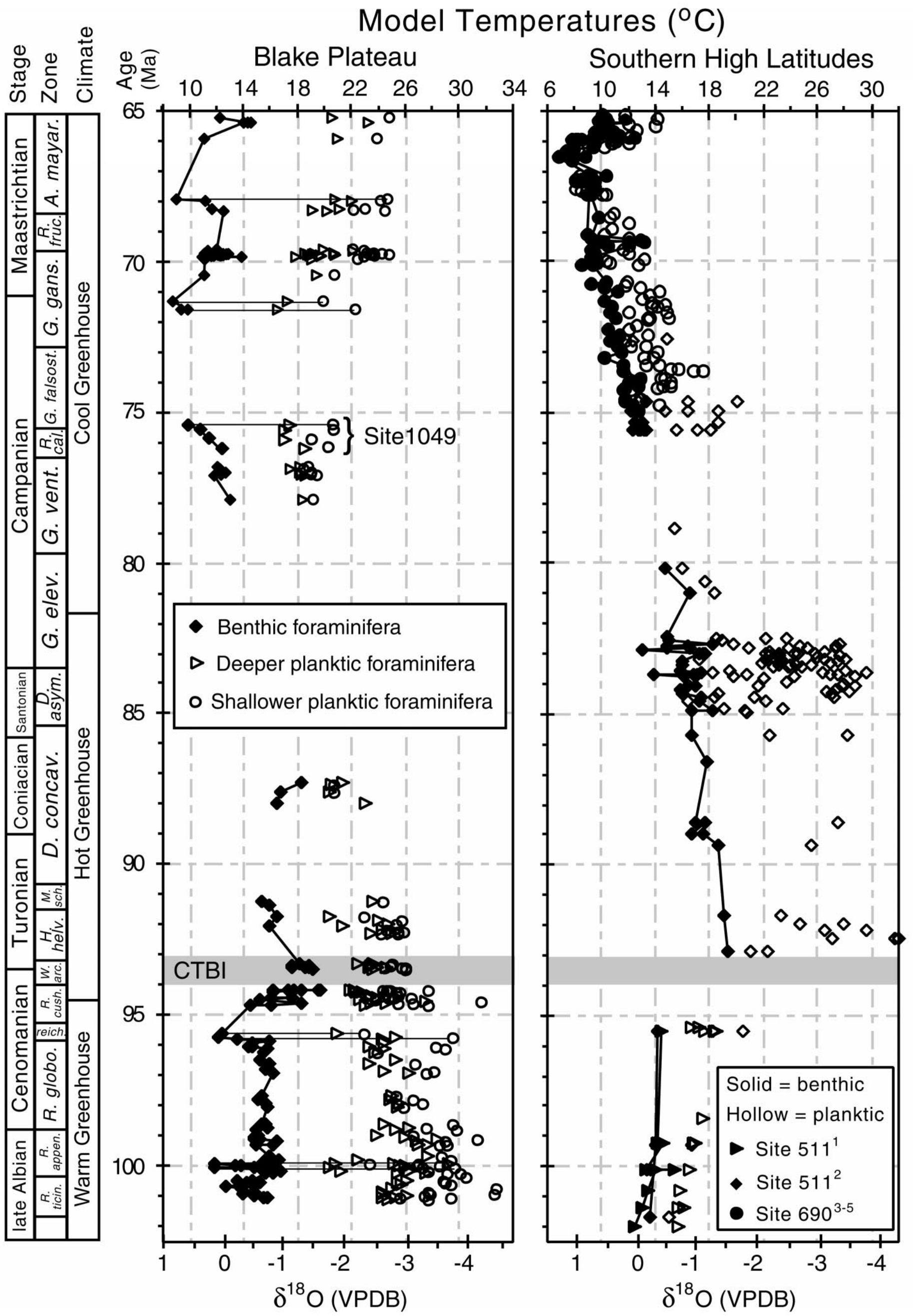

Figure 2. Model temperatures (sensu Barrera and Savin, 1999) based on $\delta^{18}O$ analyses of planktic and benthic foraminifer species from Blake Nose Site 1050, except where noted for Site 1049, and sub-Antarctic Deep Sea Drilling Project Sites 511 and 690 (VPDB is Vienna Peedee belemnite). See text for explanation of paleotemperature calculations. Horizontal lines in Blake Nose isotope record show that positive shifts in benthic $\delta^{18}O$ values are not accompanied by positive shifts in planktic data. Zonal scheme is modified from Norris et al. (1998). Sources for stable isotope data at high-latitude sites: 1—Huber et al. (1995); 2—Fassell and Bralower (1999); 3—Barrera and Huber (1990); 4—Stott and Kennett (1990); 5—Barrera and Savin (1999). See GSA Data Repository (text footnote 1) for age models, new stable isotope data, and planktic foraminiferal depth habitat assignments. Abbreviated planktic foraminiferal zones include *Rotalipora ticinensis*, *Rotalipora appenninica*, *Rotalipora globotruncanoides*, *Rotalipora reicheli*, *Rotalipora cushmani*, *Whiteinella archaeocretacea*, *Helvetoglobotruncana helvetica*, *Marginotruncana schneegansi*, *Dicarinella concavata*, *Dicarinella asymmetrica*, *Globotruncanita elevata*, *Globotruncana ventricosa*, *Radotruncana calcarata*, *Globotruncana falsostuarti*, *Gansserina gansseri*, *Racemiguembelina fructicosa*, and *Abathomphalus mayorensis*. CTBI is Cenomanian-Turonian boundary interval.

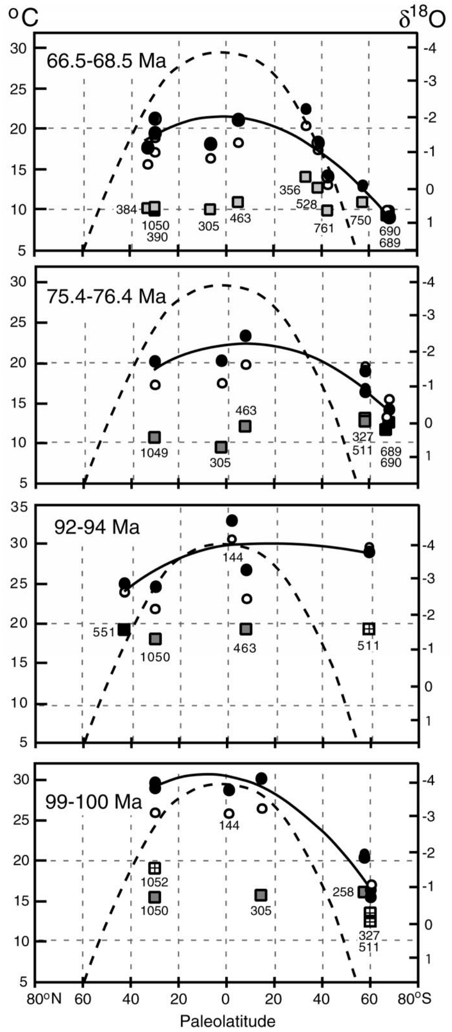

Figure 3. Latitudinal temperature gradients estimated from mean $\delta^{18}O$ values of benthic and planktic foraminifera from this and previous studies (see GSA Data Repository for references; text footnote 1). Circles represent δ_w adjusted (solid) and unadjusted (hollow) sea-surface temperature estimates from planktic foraminiferal $\delta^{18}O$ values. Squares represent $\delta^{18}O$-based temperature estimates from benthic foraminifera; density of fill patterns in squares represents relative paleobathymetry: crossed lines—upper bathyal; gray—middle bathyal; black—lower bathyal. Dashed line represents modern latitudinal temperature gradient; solid line represents best-fit second order polynomials through δ_w-adjusted planktic foraminiferal data.

planktic foraminiferal species for Site 1050, and from two benthic and three to five planktic species for the time-slice plots of Deep Sea Drilling Project (DSDP) Sites 305 and 463 and ODP Site 1049 (Fig. 3). Numerical ages assigned to the studied samples are based on age models correlated to the magnetochronology of Cande and Kent (1995). All new stable isotope data and age models reported in this study are available from the GSA Data Repository[1].

Stable isotope analyses were performed using a Finnigan MAT 252 mass spectrometer with an on-line automated carbonate reaction Kiel device at the Woods Hole Oceanographic Institution. Analytical precision was >0.07‰ for $\delta^{18}O$ and methods of data correction were

[1]GSA Data Repository item 2002008, Tables 1–7, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

described by Ostermann and Curry (2000). Sample values are reported relative to the Vienna Peedee belemnite (VPDB) standard. Paleotemperatures were calculated using the equation of Erez and Luz (1983) assuming (1) a value of $-1.0‰_{SMOW}$ for the mean isotopic composition of seawater in a nonglacial world (Shackleton and Kennett, 1975) (SMOW is standard mean ocean water), (2) that the foraminiferal calcite formed in isotopic equilibrium with Cretaceous seawater, and (3) that the Zachos et al. (1994) correction for modern-day latitudinal variation in $\delta^{18}O_{seawater}$ is appropriate to use in estimates of Cretaceous sea-surface temperatures (SSTs).

Foraminiferal shells from Blake Nose are generally well preserved, but several levels in the upper Albian and upper Cenomanian–lower Turonian of Site 1050 show significant shell recrystallization and a varying amount of calcite infilling and overgrowth (e.g., Huber et al., 1999). Such specimens were excluded from our stable isotopic study or cleaned of infilling chalk prior to stable isotopic analysis. Specimens from the other deep-sea sites discussed in this study show excellent preservation or minor to moderate shell recrystallization, and no calcite infilling or overgrowth.

RESULTS AND DISCUSSION

Late Albian–Maastrichtian Temperatures at Blake Nose

Oxygen isotope results indicate that middle bathyal waters at Blake Nose were very warm throughout the late Albian–middle Turonian, with temperatures averaging 16 °C (Fig. 2). The coolest temperatures recorded in this interval occur in the late Albian and middle Cenomanian, when bottom waters reached ~12 °C. The warmest deep-water temperatures are recorded in the latest Cenomanian and early Turonian, during which temperatures averaged 19 °C. Bottom waters continued to be very warm during the Coniacian, averaging 17 °C, then cooled to an average of 12 °C during the middle Campanian and further cooled to an average of 12 °C during the Maastrichtian. Minimum temperatures of 9 °C were recorded within the Maastrichtian at 71.2 Ma and 67.8 Ma.

Latitudinally adjusted $\delta^{18}O$ values recorded by multiple planktic species from Blake Nose provide a range of estimated temperatures of the surface waters (Fig. 2). Species yielding the most depleted $\delta^{18}O$ are assumed to best approximate SSTs, and those yielding the most enriched values are assumed to have lived close to the thermocline. Our results indicate that subtropical SSTs were similar to those of the modern day during the late Albian–Turonian and middle and late Maastrichtian, but cooler (or more enriched in ^{18}O) during the Coniacian–early Maastrichtian. Small differences in $\delta^{18}O$ values between planktic and benthic taxa during the late Cenomanian–early Turonian, Coniacian, and mid-Campanian suggest a poorly developed thermocline and strongly mixed surface waters during those times.

Paleotemperatures estimated for bottom and surface waters at Sites 511 and 690 in the sub-Antarctic are consistent with the paleotemperature history inferred for bottom waters at Blake Nose (Fig. 2). Warm conditions prevailed during the late Albian–Cenomanian and Coniacian–earliest Campanian, extreme warmth occurred during the Turonian, and the coolest temperatures were reached during the Maastrichtian.

Latitudinal Thermal Gradient Reconstructions

Time-slice comparison of oxygen isotopic data from this and previous studies permits characterization of surface- and bottom-water latitudinal temperature gradients for four well-correlated Cretaceous time intervals (Fig. 3). Whereas the number of sites that can be compared is relatively few, their broad latitudinal distribution provides better coverage than has been obtained from other climate proxies.

Despite differences in location and depth of the sites analyzed, bottom-water temperatures estimated for the time slices reveal surprising consistency across latitude and significant variation through time. For the 100–99 Ma time slice, middle bathyal paleotemperatures at all sites averaged 16 °C and differed by <1 °C. At Blake Nose, bottom waters were 3 °C cooler at middle bathyal Site 1050 than at upper bathyal Site 1052 (~1000 m shallower than Site 1050). In the 94–92 Ma time slice, mean values for bottom waters at middle bathyal sites as well as deeper Site 551 were warmer than in the late Albian, ranging from 18 to 19 °C. For the 75.4–76.5 Ma and 66.5–68.5 Ma intervals, bottom-water temperatures in all the ocean basins and across latitudes were much cooler than in the early Turonian, with estimates for most sites ranging from 9 to 11 °C.

The four Cretaceous time-slice reconstructions show SST gradients that are considerably lower than the mean modern-day SST gradient of ~0.40 °C per degree of latitude (Fig. 3). Tropical SSTs for the 99–100 Ma time slice are close to those of the modern day, but SSTs at high latitudes are much warmer than at present, resulting in an average SST gradient of 0.25 °C per degree of latitude.

The 92–94 Ma time slice indicates extremely warm northern and southern high-latitude SSTs and an asymmetrical and nearly flat thermal gradient that averaged 0.10 °C per degree of latitude. Although the benthic temperature estimates and other geological evidence indicate extreme global warmth at this time, such a uniform distribution of ocean surface temperatures is not supported by existing theories of ocean and atmospheric heat transport. Therefore, isotopic evidence for extreme polar warmth needs to be substantiated by additional high-latitude data. In the absence of evidence for significant diagenetic alteration of foraminiferal calcite at the highest latitude sites (Huber et al., 1995), regional factors affecting the oxygen isotope ratio of the ambient seawater (δ_w) could account for overestimation of high-latitude SSTs. Higher evaporation rates in the tropics would increase the δ_w of tropical surface waters while increased precipitation of isotopically depleted water would lead to ^{18}O depletion in high-latitude surface waters. This explanation is supported by climate modeling studies (e.g., Poulsen et al., 1999; Hay and DeConto, 1999) and evidence for increased storm intensity during the Cretaceous (Ito et al., 2001). In addition, surface-water $\delta^{18}O$ values at Sites 511 and 551 may have been influenced by coastal runoff of isotopically depleted precipitation from bordering emergent terrains. Such landmasses are variably depicted in different paleogeographic reconstructions (e.g., Scotese, 1997; Hay et al., 1999) because of uncertainties in the geologic record.

Tropical SSTs estimated for the 75.4–76.5 Ma and 68.5–66.5 Ma reconstructions range from 10 to 8 °C cooler than modern day SSTs at these locations. For the 75.5–74.5 reconstruction latitudinal SST gradients are quite low, averaging ~0.13 °C per degree of latitude, because of relatively warm high-latitude paleotemperatures. However, cooler high latitudes result in a higher SST gradient of ~0.22 °C per degree of latitude for the 68.5–66.5 Ma time slice. Because some shell recrystallization is evident in all foraminiferal samples from low-latitude deep-sea sites during the Campanian-Maastrichtian time intervals, diagenetic shift of the foraminiferal $\delta^{18}O$ toward more positive ratios could account for the apparent cooler than modern temperatures and diminished vertical $\delta^{18}O$ gradients (Wilson and Opdyke, 1996).

PALEOCLIMATIC AND PALEOCEANOGRAPHIC IMPLICATIONS

Our data suggest that during the late Albian to mid-Cenomanian there was a warm greenhouse climate with warm bottom waters and moderately low latitudinal thermal gradients. A transition to a hot greenhouse climate occurred in the latest Cenomanian as bottom-water temperatures reached 20 °C and temperatures at high latitudes approached those of low latitudes. This hot greenhouse state continued into the early Campanian, but was followed by a cool greenhouse climate when bottom-water temperatures dropped below 12 °C, and low-latitude surface-water temperatures dropped below those of the modern day.

Although the Blake Nose record suggests bottom-water cooling excursions of 3–5 °C at several middle through Late Cretaceous intervals, SST estimates from these same intervals do not exhibit changes that parallel the deep-water temperature trends, which would be expected if changes in the $\delta^{18}O$ composition of global seawater had occurred during those times. Short-term variability observed among planktic $\delta^{18}O$ values on Blake Nose (MacLeod et al., 2001; Wilson and Norris, 2001) suggests that high-resolution sampling might increase the range of SSTs estimated for Site 1050. However, even high-frequency $\delta^{18}O$ variation should be correlated with benthic $\delta^{18}O$ excursions if there were a shift in $\delta^{18}O_{seawater}$ or true global cooling. In addition, late Albian–Maastrichtian bottom waters and high-latitude surface waters seem too warm to be compatible with the ice-sheet scenarios proposed by Miller et al. (1999) and Stoll and Schrag (1996, 2000).

The time-slice reconstructions for the late Albian, mid-Campanian, and late Maastrichtian show that surface- and bottom-water temperatures intersect at southern high latitudes, suggesting that the south polar region was a primary source of bottom-water formation during those times. However, the reconstruction for the late Cenomanian–early Turonian shows no convergence of bottom- and surface-water temperatures and, therefore, no evidence for deep-water convection at high latitudes. The large vertical $\delta^{18}O$ gradients and extreme warmth at high latitudes, warm bottom-water temperatures, and maximum flooding of continental interiors during the late Cenomanian–early Turonian point to the most favorable conditions for deep-water formation at low latitudes of any time during the past 250 m.y. Additional information, including carefully scrutinized stable isotopic and other paleoclimatic proxy data, from this supergreenhouse period is needed to better understand the dynamics of an ocean-climate system that was so different from that of today.

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