Did the rifting of the Atlantic Ocean cause the Cretaceous thermal maximum?

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ABSTRACT

The Cretaceous thermal maximum was a major turning point in the history of Earth's climate. This interval of peak warmth in the Turonian has been attributed to very high atmospheric pCO$_2$ resulting from rapid outgassing rates, although crustal cycling rates peaked in the Aptian–Albian interval. On the basis of coupled ocean-atmosphere model simulations of the middle Cretaceous, we hypothesize that the formation of an Atlantic gateway could have contributed to the Cretaceous thermal maximum. Differences between prerifting and postrifting climate experiments demonstrate substantial regional oceanographic changes in the North and South Atlantic Basins that are consistent with oxygen isotopic evidence used to infer a Cretaceous thermal maximum. The model results help reconcile the paleoclimate record inferred from foraminiferal δ^{18}O with our understanding of climate dynamics and Cretaceous tectonism.

Keywords: Cretaceous, paleoclimate, general circulation models, rifting, Atlantic Ocean.

INTRODUCTION

Variations in atmospheric carbon dioxide concentrations have been implicated as a major driver of long-term climate change. However, discrepancies between pCO$_2$ and climate proxies suggest that during certain intervals of Earth's history pCO$_2$ variability was not the primary control on climate change (e.g., Veizer et al., 2000). Similarly, mid-Cretaceous records of δ^{18}O in foraminiferal calcite signal an episode of global warming that commenced in the early Albian and culminated in the early to middle Turonian with the Cretaceous thermal maximum, the warmest climate conditions in more than 144 m.y. (Clarke and Jenkyns, 1999; Huber et al., 2002; Wilson et al., 2002). However, global rates of ocean-crust cycling, and by inference the CO$_2$ flux to the atmosphere, peaked in the Aptian–Albian (Larson, 1991). Moreover, reconstructions of paleo-pCO$_2$ generally support a reduction in atmospheric pCO$_2$ through the mid-Cretaceous, although the range of paleo-pCO$_2$ estimates varies from $<$900 to $>$5000 ppmv (see summary in Bice and Norris, 2002).

Although the general warmth of the Cretaceous is attributed to elevated levels of atmospheric CO$_2$ (Barron and Washington, 1985), the cause of the Cretaceous thermal maximum is unknown. Despite the apparent reduction in pCO$_2$ through the mid-Cretaceous, a rapid increase in atmospheric pCO$_2$, perhaps resulting from a ''hidden'' Turonian pulse in crustal cycling, has been postulated (Wilson et al., 2002; Bice and Norris, 2002). In order to match Turonian sea-surface paleotemperature estimates, an atmospheric general circulation model (GCM) with a slab-ocean model requires atmospheric pCO$_2$ of 4500–7500 ppm, a value ~12–20 times greater than the modern and more than twice that estimated for the Albian–Cenomanian interval (Bice and Norris, 2002).

In addition to high outgassing rates, another consequence of vigorous Cretaceous tectonism was the rifting of South America and Africa. Surface flow between the North and South Atlantic probably began in the Albian with the development of the Equatorial Atlantic gateway (e.g., De Matos, 1999; Wagner and Pletsch, 1999). After this early opening stage, the gateway evolved into isolated deep basins with restricted deep-water circulation. As rifting continued through the Cenomanian, the basins aligned to form a continuous deep-water connection through the Equatorial Atlantic gateway with a depth of at least 2000 m (Wagner and Pletsch, 1999). In this study we present results from coupled ocean-atmosphere simulations of prerifting (early Albian) and postrifting (Turonian) intervals in the mid-Cretaceous. This sensitivity study demonstrates that tectonic forcing could have led to a major reorganization of the ocean circulation and regional climate changes consistent with the oxygen isotopic evidence used to infer a Cretaceous thermal maximum.

MODEL DESCRIPTION

The model experiments were completed using the fast ocean-atmosphere model (FOAM), a fully coupled ocean-atmosphere GCM. The atmospheric component of FOAM version 1.4 is a parallelized version of Community Climate Model 2 (CCM2) of the National Center for Atmospheric Research with the upgraded CCM3 physics from version 3.6. The atmospheric model contains 18 vertical levels and a horizontal resolution of R15 ($4.5° \times 7.5°$). The ocean component (OM3) is dynamically similar to the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model (MOM). OM3 contains 16 vertical layers and uses a 128×128 point grid ($1.4° \times 2.8°$). A coupler links the ocean and atmospheric models (Jacob, 1997).

Two mid-Cretaceous simulations were developed for this study. The only difference between the experimental designs was the presence or absence of a gateway between the Atlantic Oceans. Grid cells connecting South America and Africa in the prerifting experiment were increased to a depth of 3000 m in the postrifting experiment. In all other respects, the boundary and initial conditions were identical. The model geography and topography were based on an Albian paleogeography (Scotese, 2001). Model bathymetry was created by applying an age-depth relationship to regions with known magnetic lineations (Barron, 1987). Elsewhere, open ocean depths were specified as 5000 m; continental shelves were set to 200 m. In order to close the hydrological cycle, continental drainage basins were developed based on the mid-Cretaceous topography. The atmospheric CO$_2$ concentration was set to 1380 ppm, approximately four times preindustrial values. Earth orbital parameters were set to present-day values. The solar luminosity was specified as 99% of modern (Gough, 1977). In the absence of detailed data sets of Cretaceous biomes, surface types were set to average model surface characteristics (i.e., deciduous forest).

No flux corrections or acceleration techniques were employed. Initial conditions for the ocean model included uniform, warm seawater temperatures, ranging from 28.0 °C at the surface to 6.0 °C at 5000 m depth, and a uniform seawater salinity of 34.8. Each simulation was integrated for 450 model years. All model results have been averaged over the last 25 model years.

MARINE δ^{18}O DATA

Marine δ^{18}O data were compiled from the literature (Table 1). The main criterion in choosing the data was the availability of a time series spanning the Albian and Turonian. Except for planktonic fora-

TABLE 1. SUMMARY OF REPORTED $\Delta\delta^{18}$O DATA FOR THE MIDDLE CRETACEOUS INTERVAL AND COMPARISON WITH MODEL-INFERRED $\Delta\delta^{18}$O

Location	Source	Age	Paleo-depth	ΔT	$\Delta\delta^{18}$O	Model $\Delta\delta^{18}$O
DSDP Site 511	Huber et al. (1995)	Albian–Turonian	Shallow	~10	−2.00	−0.35
DSDP Site 511	Huber et al. (1995)	Albian–Turonian	Lower to upper bathyal	~7.5	−1.50	−0.50
DSDP Site 144	Wilson et al. (2002)	late Albian–Turonian	Shallow	~5	−1.00	−0.50
Exmouth Plateau	Clarke and Jenkyns (1999)	early Albian–middle Turonian	Shallow	~3.5†	−0.70	−0.20
ODP Site 1050	Huber et al. (2002)	late Albian–early Turonian	Shallow	0	0.00	−0.20
ODP Site 1050	Huber et al. (2002)	late Albian–early Turonian	Middle bathyal	~2.5	−0.50	−0.30
Israel	Kolodny and Raab (1988)	Aptian/Albian–Turonian	Shallow	~3.0	−0.60	−0.30
Southern England	Jenkyns et al. (1994)	late Albian–Turonian	Shallow	~2.5†	−0.50†	−0.35
Italy	Jenkyns et al. (1994)	Albian–Turonian	Shallow	~2.5†	−0.50†	−0.25
DSDP Site 463	Clarke (2001; personal communication, 2002)	late Albian–early Turonian	Shallow	~1.5*	−0.30	−0.10

Note: The model-inferred $\Delta\delta^{18}$O was calculated from the model-inferred change (postrifting experiment minus prerifting experiment) in salinity (S) and temperature (T) at the grid cell corresponding to the site location. The following relationships were used in the calculation of $\Delta\delta^{18}$O: $\Delta\delta^{18}O_{\text{low latitudes}} = 0.2\ (\Delta S) - 0.2\ (\Delta T)$, and $\Delta\delta^{18}O_{\text{high latitudes}} = 0.5\ (\Delta S) - 0.2\ (\Delta T)$, where low-latitude sites include all locations in the North Atlantic Basin and Mediterranean Tethys, and high-latitude sites include all locations in the Southern Ocean (Deep Sea Drilling Project, DSDP Site 511 and Exmouth Plateau). The relationship between salinity and δ^{18}O of seawater varies with latitude, but is ~0.5‰ psu^{-1}at mid and high latitudes (Broecker, 1989; Schmidt, 1999), and 0.1–0.3‰ psu^{-1}at low latitudes (Fairbanks et al., 1997). The relationship between temperature and δ^{18}O of seawater was approximated as 0.2‰ °C^{-1}(Bemis et al., 1998). ODP—Ocean Drilling Program.

*δ^{18}O from fine-fraction carbonate.

†δ^{18}O from bulk carbonate.

minifera from Ocean Drilling Program Site 1050, all sites exhibited depletion in δ^{18}O consistent with a warming through the mid-Cretaceous.

MODEL RESULTS

With elevated atmospheric CO$_2$ levels, the Cretaceous experiments have a global average sea-surface temperature (SST) of ~20 °C, ~2 °C warmer than present-day SSTs. Maximum SSTs in the tropics are >33 °C; minimum temperatures in the Arctic Ocean are <1 °C. On a global scale, the opening of the Atlantic gateway leads to a very slight warming. Global average, mean-annual, sea-surface and near-surface air temperatures increase by 0.17 °C and 0.13 °C, respectively. The surface warming is attributed to a slight increase (0.25 W/m^2) in global greenhouse forcing, resulting from a slightly more vigorous hydrological cycle.

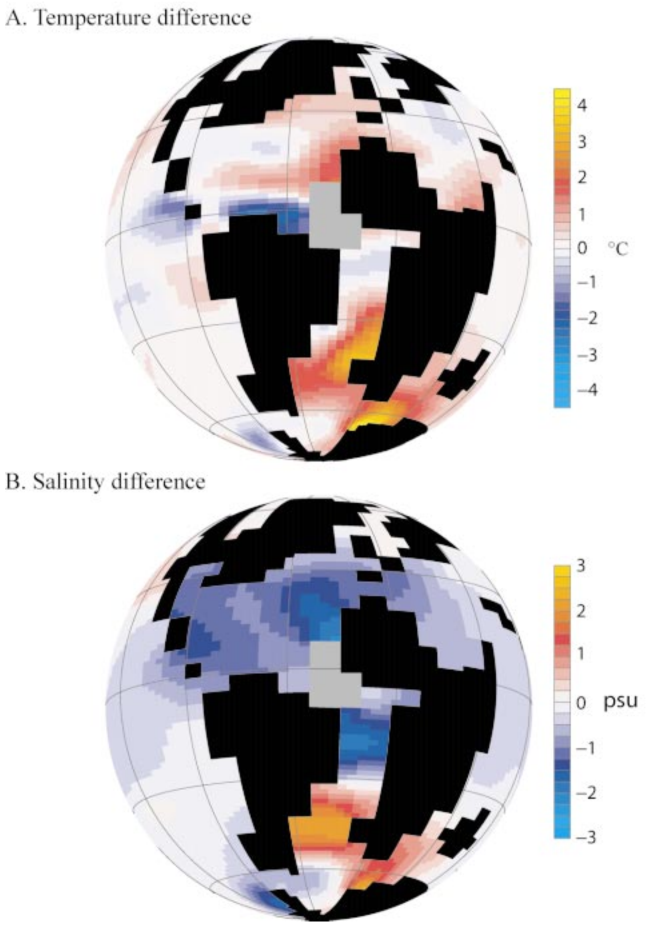

Figure 1. Mean annual upper ocean (0–30 m) temperature (°C) and salinity (practical salinity units, psu) difference between postrifting and prerifting Cretaceous experiments. Black shading indicates Cretaceous continents; gray shading marks grid cells that are depressed in postrifting experiment.

Regional scale climate changes in the Atlantic basins are remarkable. Figure 1 illustrates the shallow (0–30 m) temperature and salinity changes caused by the initiation of an Atlantic gateway. The North Atlantic and northern South Atlantic upper ocean is characterized by widespread freshening by as much as 2.25 psu. In contrast, the southern South Atlantic is marked by a salinity increase. Changes in seawater characteristics are largely linked to changes in the upper ocean circulation. The opening of the Equatorial Atlantic gateway has two important effects on the North Atlantic shallow circulation. First, divergence caused by the initiation of flow from the North Atlantic to the South Atlantic causes flow from the eastern Pacific to reverse (i.e., flow eastward), advecting relatively cool water into the Atlantic (Fig. 2).

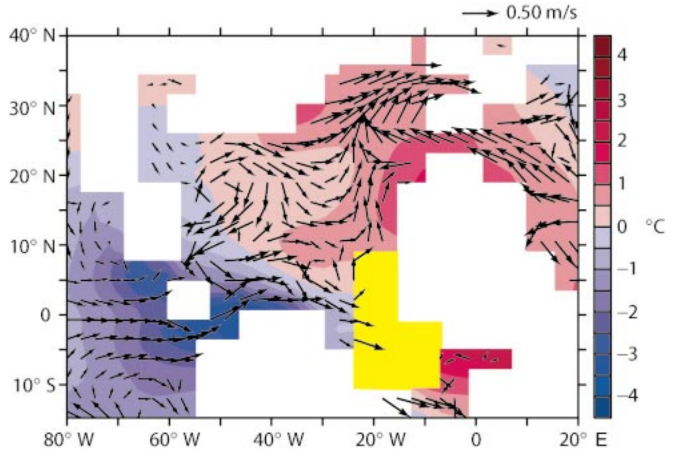

Figure 2. Difference between postrifting and prerifting flow (vectors) and seawater temperature (colored contours) in upper 300 m. Continents are shown as unshaded (white) regions; yellow shading demarks grid cells that are depressed in postrifting experiment. Note increased flow into North Atlantic basin from Pacific Ocean. Change in circulation causes increase in heat import into North Atlantic from western Pacific Ocean, and decrease in heat export to eastern Pacific Ocean.

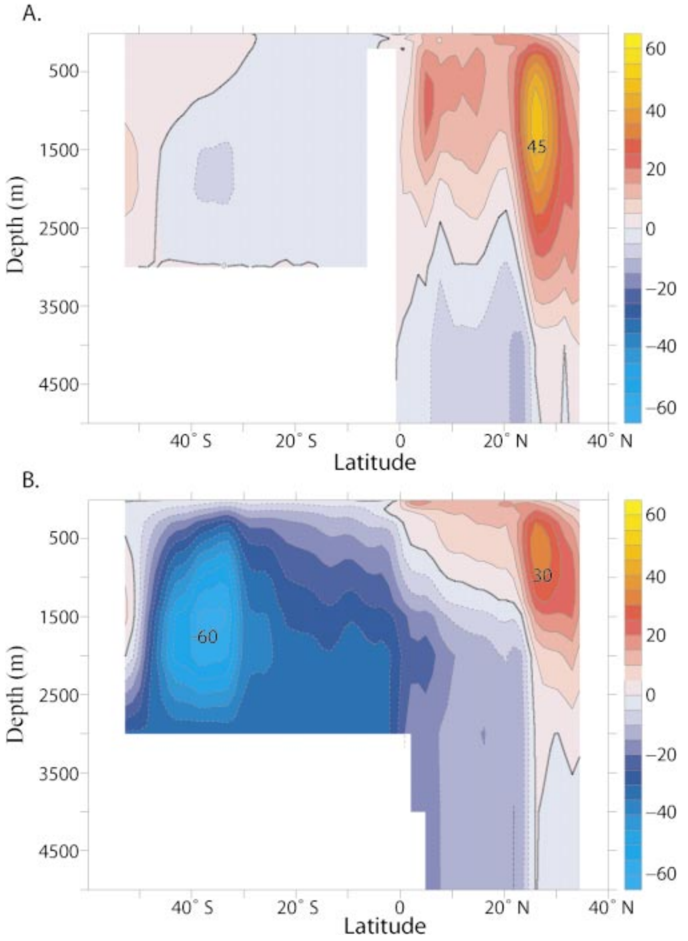

Figure 3. Meridional overturning (Sv = 10^6 m^3 s^{-1}) in North and South Atlantic Oceans for (A) prefitting and (B) postrifting experiments. Positive overturning (warm colors) represents clockwise transport and vice versa. (Appearance of shallow connection between Atlantic basins in A is artifact of zonal integration in overturning calculation.)

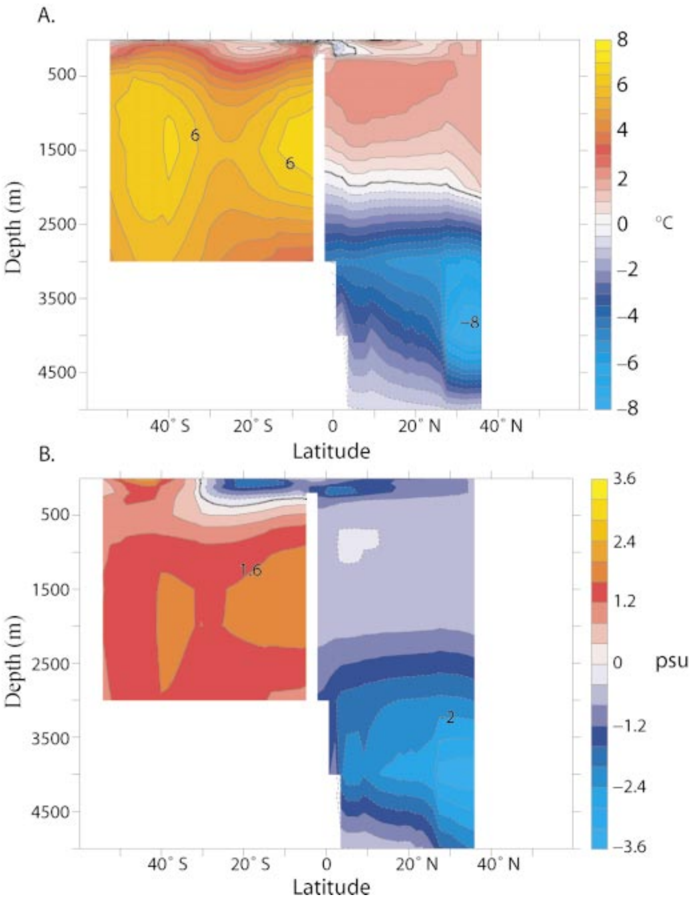

Figure 4. Mean annual, zonally averaged (A) temperature (°C) and (B) salinity (psu, practical salinity units) difference in Atlantic Ocean between postrifting and prefitting Cretaceous experiments. Opening of Atlantic gateway and initiation of flow between Atlantic basins lead to considerable changes in temperature and salinity. (Appearance of shallow connection between Atlantic basins is artifact of zonal averaging.)

Second, the locus of atmospheric convection in the North Atlantic shifts from the south-central Atlantic to northwestern Africa. The development of atmospheric convection over northwestern Africa drives a cyclonic wind that enhances the westward wind stress over parts of the northern North Atlantic Ocean. In response, shallow flow of relatively warm water from the western Pacific to the Atlantic is enhanced (Fig. 2).

The rifting of the gateway also causes a reorganization of the deep circulation. In the prerifting experiment, vigorous anticyclonic (clockwise) circulation characterizes the North Atlantic with little meridional circulation in the South Atlantic (Fig. 3A). In the postrifting experiment, a well-developed cyclonic (counterclockwise) gyre circulates through the Atlantic basins (Fig. 3B). In conjunction with these changes in circulation, warm, saline upper ocean waters from the North Atlantic are exported into the South Atlantic and replaced by cooler, fresher South Atlantic waters at depth (Fig. 4). An important consequence of these circulation changes is a shift in the salinity balance of the ocean basins, and the freshening of the North Atlantic (Figs. 1B and 4B).

The oceanographic changes described here are considerable, and can explain much of the changes in the $\delta^{18}O$ record of marine carbonate between the Albian and Turonian. Table 1 summarizes the $\delta^{18}O$ and interpreted paleotemperature change associated with the transition to the Cretaceous thermal maximum. Table 1 also reports the $\Delta\delta^{18}O$ predicted on the basis of the temperature and salinity changes between the prerifting and postrifting experiments. In 9 of 10 cases, including shallow and deep locations, the sign of $\Delta\delta^{18}O$ is consistent between the observations and the model. In most cases, the magnitude of the model-inferred $\Delta\delta^{18}O$ explains at least one-third of the observed $\Delta\delta^{18}O$. At most sites, particularly those in the North Atlantic, the model-inferred $\Delta\delta^{18}O$ is largely the result of a decrease in salinity (signifying a shift to waters depleted in ^{18}O).

DISCUSSION AND CONCLUSIONS

The comparison of observed and model-inferred $\Delta\delta^{18}O$ values is complicated by uncertainties associated with $\delta^{18}O$ paleothermometry and paleoclimate modeling. Many of these issues, including uncertainties in the isotopic composition of seawater, the paleohabitat of the foraminifera, the magnitude of $\delta^{18}O$ offsets between species, and ontogenetic offsets, as well as paleoclimate modeling limitations and the influence of diagenetic alteration and seawater pH on foraminiferal $\delta^{18}O$, have been discussed in detail (e.g., Poulsen et al., 1999, 2001; Zeebe, 2001; Wilson et al., 2002). It is likely that many of these records, particularly those based on chalks, have been influenced by fine-scale recrystallization of the calcite. However, the differential $\delta^{18}O$ between samples is likely retained (Pearson et al., 2001). For this reason, we have not made site-by-site comparisons between the marine $\delta^{18}O$ and the model for a specific time slice (i.e., Albian or Turonian).

Additional uncertainties include the use of average, modern relationships between ΔS (salinity difference), Δ*T* (temperature difference), and $\Delta\delta^{18}O$. It is well known that the relationship between ΔS and $\delta^{18}O$ varies considerably with latitude, but can also exhibit substantial regional variations (see summary in Zachos et al., 1994). In light of these uncertainties, we emphasize the consistency between the model-inferred and observed $\delta^{18}O$ at all sites, rather than the magnitude of $\Delta\delta^{18}O$ at individual sites.

The model results demonstrate that a substantial portion of the $\delta^{18}O$ depletion in foraminiferal calcite can be explained by regional climate change, in the absence of significant global warming. Regional differences in the model-inferred $\Delta\delta^{18}O$ resulting from the opening of the Equatorial Atlantic gateway are consistent with observed regional differences in $\Delta\delta^{18}O$. For example, the model and the observations demonstrate smaller $\Delta\delta^{18}O$ in the low-latitude Pacific than in the low-latitude Atlantic, and larger $\Delta\delta^{18}O$ from Deep Sea Drilling Project (DSDP) Site 411 than other cores in the North Atlantic (Table 1).

If modern and Cretaceous relationships between ΔS, Δ*T*, and $\Delta\delta^{18}O$ were similar, the magnitude of the model-inferred $\Delta\delta^{18}O$ indicates that the initiation of the Equatorial Atlantic gateway may not fully account for the change in foraminiferal $\delta^{18}O$ leading to the Cretaceous thermal maximum. A modest rise in atmospheric CO_2 through increased submarine volcanic activity could be one resolution to this discrepancy, and is supported by a long-term rise in sea level that peaked in the early Turonian (Wilson et al., 2002). The primary argument for a substantial increase in atmospheric CO_2 comes from the planktonic foraminferal $\delta^{18}O$ record from a single site, DSDP Site 511 on the Falkland Plateau, interpreted to represent ~10 °C warming (Bice and Norris, 2002). In the model, Site 511 is situated between two water types, South Atlantic and Southern Ocean surface waters, with very different temperature and salinity (and, by inference, $\delta^{18}O$) characteristics. Gateway rifting resulted in an inferred 0.35‰ decrease in $\delta^{18}O$, caused by the incursion of low salinity (isotopically depleted) water from the Southern Ocean into the South Atlantic. Additional encroachment of Southern Ocean water in the southern South Atlantic, perhaps as a result of geographic changes in these basins, could account for the mid-Cretaceous decrease in foraminiferal $\delta^{18}O$.

In addition to the regional $\delta^{18}O$ changes described here, the opening of the gateway in the model initiated vigorous circulation between the North and South Atlantic Oceans and substantial changes in seawater temperature and salinity (Figs. 3 and 4). These large oceanographic changes should be preserved in the geological record. In fact, the mid-Cretaceous interval was marked by dramatic changes in the marine environment, including the occurrence of oxygen anoxic event 2 (Arthur et al., 1987), the collapse of Caribbean reefs (Johnson et al., 1996), and changes in the carbonate saturation state of the oceans (Thierstein, 1979) that may be consistent with profound changes of the Atlantic Ocean circulation (Poulsen et al., 2001). The consistency between geological observations and climate model simulations supports the hypothesis that the Cretaceous thermal maximum was at least partly the climatic expression of a tectonically driven oceanographic event.

ACKNOWLEDGMENTS

We gratefully acknowledge the technical support of W. Peterson and the use of advanced computing resources at Penn State's Earth and Mineral Science Environmental Institute. L. Clarke generously provided unpublished isotopic data from Site 463. We also thank K. Bice, B. Huber, and P. Wilson for constructive comments that improved this report. A. Gendaszek received financial support from the University of Southern California's Department of Earth Sciences and the Duncan Stuart Fund.

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Manuscript received 24 June 2002
Revised manuscript received 2 October 2002
Manuscript accepted 7 October 2002

Printed in USA