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Calcareous nannofossil evidence for the existence of the Gulf Stream during the late Maastrichtian

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[1] Upper Maastrichtian calcareous nannofossil assemblages, from eight cores on the South Carolina Coastal Plain (onshore set) and three deep sea drilling sites from the continental slope and abyssal hills (offshore set), were analyzed by correlation and principal component analysis to examine the ancient surface water thermal structure. In addition, a temperature index derived from independently published paleobiogeographic information was applied to the sample data. All three methods indicate a strong separation of the samples into onshore and offshore sets, with the offshore data set exhibiting significantly warmer paleotemperatures. The great disparity between these two sample sets indicates that there was a strong thermal contrast between the onshore and offshore surface water masses that persisted throughout the late Maastrichtian despite evident short-term changes in fertility, productivity, and community structure. This suggests the Gulf Stream was present as a major oceanographic feature during the late Maastrichtian.

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1. Introduction

[2] The Gulf Stream is one of the most prominent oceanographic features in the modern North Atlantic. The age of this western boundary current is uncertain. Analyses of high-resolution seismic reflection profiles, drill hole data, and dredge hauls show that the geologic history of the continental margin south of Cape Hatteras was controlled largely by easterly flow of Gulf of Mexico water through the Suwannee Straits or by the northeasterly flow of the ancient Gulf Stream. Evidence of bottom scour in the Florida Straits suggests that sporadic initiation of the northeasterly flowing Florida Current may have occurred as early as the middle Cenomanian [*Sheridan et al.*, 1981]. During the Late Cretaceous, flow from the Gulf of Mexico across southern Georgia and northern Florida (the "Suwannee Strait" of *Hull* [1962]) may have contributed additional volume to a nascent Gulf Stream. *Pinet and Popenoe* [1985a] postulated that this hybrid flow may have persisted into the late Paleocene or early Eocene, at which point the Gulf Stream, in the modern sense, became firmly established [*Uchupi*, 1967; *Pinet and Popenoe*, 1985b]. Interaction between the cross-shelf Suwannee Strait current and the northeasterly trending Gulf Stream current remains unclear.

[3] Currently, as the Gulf Stream flows northeastward over the continental shelf of the North American Atlantic Coast, it separates cold Slope water to the north and west from the warm waters of the Sargasso Sea to the south and east, creating a prominent temperature contrast (Figure 1). Given the stable, geostrophic nature of the North Atlantic Gyre, it is probable that this temperature contrast is a feature that has characterized the Gulf Stream, to some degree, since its inception. This strong thermal contrast would exert a dominant control over the phytoplankton populations inhabiting the area, and should thus be detectable from the fossil record.

2. Paleoecological Background

[4] There is good reason to believe that calcareous nannofossils were reliable indicators of surface water temperatures in the geologic past. The distribution of modern coccolithophores indicates that the presence and relative abundance of species are related to the thermal structure of surface waters. Modern coccolithophore distributions in the Atlantic Ocean can be divided into seven biogeographic zones, the boundaries of which are roughly subparallel to latitude [*McIntyre and Bé*, 1967; *Okada and McIntyre*, 1977, 1979]. Coccolithophore biogeographic zones in the Pacific show a similar, latitude-parallel distribution [*Okada and Honjo*, 1973, 1975; *Honjo and Okada*, 1974; *Roth and Berger*, 1975; *Okada and McIntyre*, 1977]. One notable exception to the latitude-parallel trend occurs in the northwestern Atlantic in association with the Gulf Stream. Tropical assemblages are deflected north to northeastward along the edge of the continental shelf of the United States, while assemblages from the Subarctic biogeographic zone are deflected southwest along the inner continental shelf of Maritime Canada and the northeastern United States [*McIntyre and Bé*, 1967].

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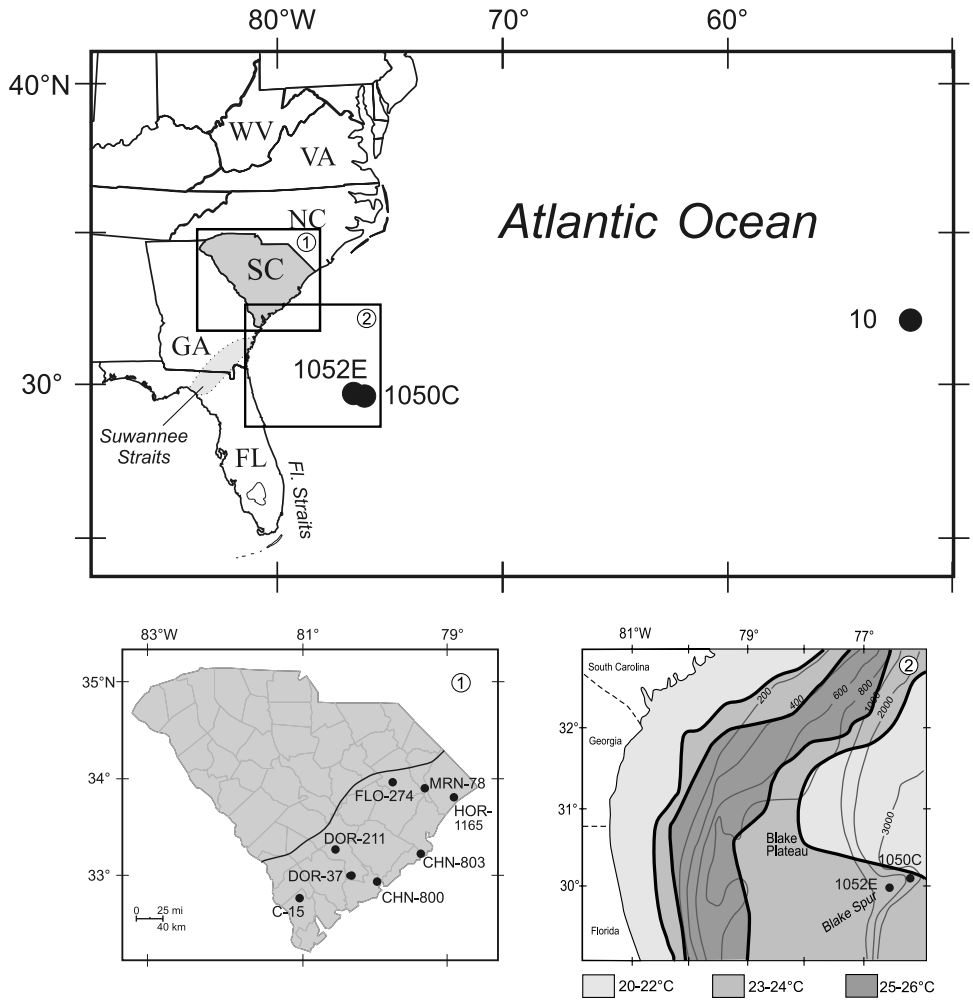

Figure 1. Locations of cores used in this study. Inset map 1 of South Carolina illustrates the distribution of the onshore data set. The solid line indicates the location of the paleoshoreline during the late Maastrichtian. The offshore data set consists of samples from Ocean Drilling Project Holes 1050C and 1052E and from Deep Sea Drilling Project Site 10. Inset map 2 shows current sea surface temperatures for the Blake Plateau region. Note the decrease in water temperature in the nearshore region. Data were obtained by the Naval Research Laboratory MODAS 2.1 website (available at www.7320.nrlssc.navy.mil/altimetry/images/).

[5] Quaternary studies have utilized the biogeographic partitioning of coccolith assemblages to reconstruct climate change during the northern hemisphere glaciation [*Ruddiman and McIntyre*, 1976; *Geitzenauer et al.*, 1977]. Examination of Neogene oceanic assemblages indicates the close correspondence of shifts in coccolith distribution patterns to climatic change during the Pliocene [*Backman et al.*, 1986] and the Miocene [*Haq*, 1980]. *Haq and Lohmann* [1976] examined the paleogeographic distribution of calcareous nannofossils for twelve time slices through the Paleogene of the Atlantic Ocean. A clear separation of assemblages by paleolatitude indicates segregation was related to latitudinal surface water temperature gradients. *Haq and Lohmann* [1976] used shifts in the distribution of high- and low-latitude assemblages through time to construct a paleotemperature history for the Paleogene. This coccolith-derived paleotemperature history correlates strongly with subsequently compiled oxygen isotope paleotemperature records [e.g., *Zachos et al.*, 2001], indicating that assemblage distribution is a reliable indicator of oceanic surface water thermal structure.

[6] Studies from the Cretaceous document the persistence of the latitudinal distribution of calcareous nannofossil assemblages. *Worsley and Martini* [1970] first recognized the antithetic behavior of two biostratigraphically important species in the upper Maastrichtian, with *Micula murus* restricted to low paleolatitudes and *Nephrolithus frequens* abundant only at high latitudes. *Bukry* [1973] discussed the distinctive character of northern high-latitude assemblages including the absence of previously supposed "ubiquitous" species *Watznaueria*

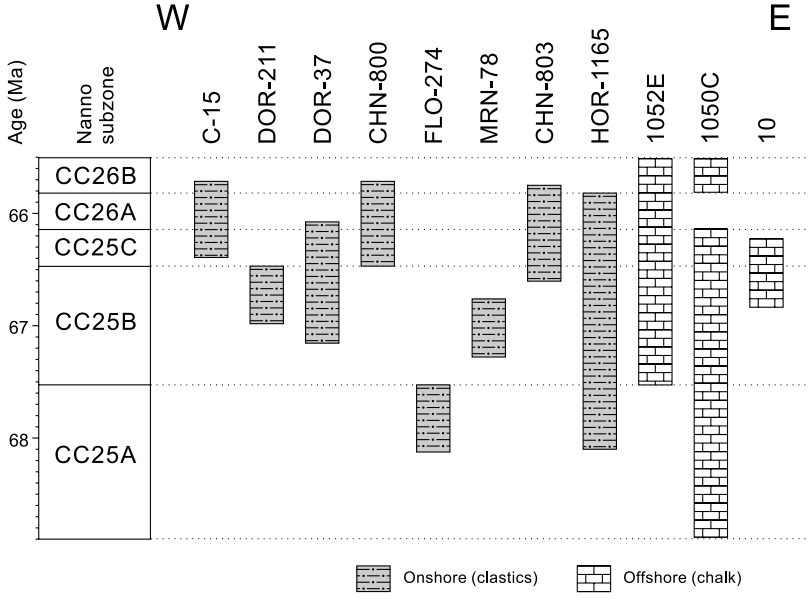

Figure 2. Biochronological placement of the study sections based on the graphic correlation solution of *Self-Trail* [2001]. Calcareous nannofossil biostratigraphy of the study cores is expressed in terms of the zonation of *Sissingh* [1977] and *Perch-Nielsen* [1985]. Geochronological age estimates (in Myr) are based on age assignments of subzonal biohorizons given by *Erba et al.* [1995]. These age assignments have been adjusted in accordance with the estimates for the beginning and end of the Maastrichtian Age by *Gradstein et al.* [2004].

barnesiae. *Thierstein* [1976] defined the latitudinal distribution of several taxa, and subsequently refined species latitudinal affinities by quantitative study of 118 upper Maastrichtian samples [*Thierstein*, 1981]. Ocean drilling in the southern high latitudes led to a series of papers that documented several high-latitude species as well as discussing the characteristic nature of these assemblages [*Wise and Wind*, 1977; *Wind*, 1979; *Wise*, 1983; *Pospichal and Wise*, 1990; *Watkins*, 1992; *Watkins et al.*, 1996]. *Lees* [2002] illustrated latitudinal distribution of assemblages in a semiquantitative study of the Upper Cretaceous Indian Ocean nannofossils.

3. Material and Methods

[7] The strong thermal contrast imposed by the modern Gulf Stream is a function of the large-scale transport of warm Gulf of Mexico and Caribbean water northeastward by this western boundary current (Figure 1). This characteristic feature of the Gulf Stream can be used as an indicator of its existence in the fossil record. A set of 172 upper Maastrichtian samples collected along an east-west transect (Figure 1) were analyzed to ascertain whether a clear paleotemperature contrast was present during the latest Cretaceous. For the sake of discussion, these samples can be divided conveniently into an onshore set and an offshore set.

[8] The onshore set of samples is derived from eight cores from the Atlantic Coastal Plain (Figure 1; USGS cores C-15, CHN-800, CHN-803, HOR-1165, MRN-78, FLO-274, DOR-37, and DOR-211) from the upper Maastrichtian Peedee Formation, which consists predominantly of fine-grained, massively bioturbated clayey sandstone interbedded with massive, slightly sandy, silty carbonate-rich clay stone. The Peedee is rich in calcareous microfossils, and examination of benthic foraminifera and ostracode assemblages suggests deposition in middle to outer neritic paleodepths [*Edwards et al.*, 1999; *Self-Trail and Gohn*, 1996; *VanNieuwenhuise and Kanes*, 1976]. The thickness of the Peedee Formation ranges from 20 m to 70 m. The Peedee Formation is bounded disconformably at its base by the upper Campanian Donoho Creek Formation and at its top by either the lower Paleocene Rhems Formation or Pleistocene sands. The basal Peedee is massively reworked and consists of a lag deposit rich in phosphate pebbles, bone fragments, and quartz pebbles that decrease in size up section [*Self-Trail et al.*, 2002].

[9] The offshore sample set is derived from Ocean Drilling Program (ODP) sites 1050 and 1052 (Blake Nose) and Deep Sea Drilling Project (DSDP) site 10 (western North Atlantic; Figure 1). The Blake Nose material consists primarily of calcareous nannofossil clay stones and chalks rich in foraminifers and moderately to heavily bioturbated [*Norris et al.*, 1998]. These sites lie on the eastern edge of the Blake Plateau with Cretaceous paleodepths (based on foraminiferal assemblages) of upper bathyal at Site 1052E to lower upper bathyal at Site 1050C [*Norris et al.*, 1998]. The base of the upper Maastrichtian is disconformable in Hole 1050C and a minor disconformity is present in the upper Maastrichtian of Hole 1052E [*Self-Trail*, 2002].

[10] The calcareous nannofossil biostratigraphic framework for these sites (Figure 2) is based on the detailed study of the onshore cores and ODP Sites 1050 and 1052 by *Self-Trail* [2001]. Placement of these sections within this framework is based on a graphic correlation solution using ODP Hole 1052E as a standard reference section. The placement of DSDP Site 10 in the framework is based on comparison with the composite standard reference section of *Self-Trail* [2001].

[11] Samples were chosen for good preservation and stratigraphic distribution in the upper Maastrichtian calcareous nannofossil zones CC25 and CC26. Onshore samples were subjected to a gravitational settling procedure to remove coarse sand-sized grains which would have otherwise dominated the smear slides. Samples from the offshore sites were made using traditional smear slide techniques. Population counts of 450 calcareous nannofossil specimens per smear slide were made along random traverses using a Zeiss Photomicroscope 3 at 1250 times magnification. Additional fields of view were examined in order to identify rare specimens useful for biostratigraphy. All zeugrhabdotids <5 μm were combined under the taxon designation *Zeugrhabdotus* small spp., and those >5 μm were designated as *Zeugrhabdotus* large spp. Nannofossil assemblage data are archived at the World Data Center-A for Paleoclimatology and can be accessed at ftp://ftp.ncdc.noaa.gov/pub/data/paleo/contributions_by_author/watkins2005/.

[12] Nannofossil census data were analyzed by several methods. Species richness and Shannon diversity were calculated directly from species relative abundance data. Correlation, principal components analysis, and analysis of variance of set populations were performed using PAST [*Hammer et al.*, 2001] and the Systat statistical packages. These three analytical techniques were used on raw proportion data as well as log-transformed proportion data. The analyses of raw and log-transformed data sets yielded results that did not significantly differ. For this reason, only the results from the analyses of raw proportional data are reported.

4. Results

[13] The calcareous nannofossil assemblages are well-preserved and diverse, with a total of 142 species recognized and counted from 162 samples. Average species richness for the counts of 450 specimens is 60 species, with a minimum of 43 species and a maximum of 80 species. Shannon diversity values vary from 2.37 to 3.70, with an average value of 3.25. There is no significant differentiation between samples in onshore and offshore environments ($F = 2.51$, $p = 0.115$) and there is no clear variation of the values with time through the sampled interval.

[14] Examination of the calcareous nannofossil data indicates that the assemblages are dominated by three primary taxa (*Micula decussata*, *Watznaueria barnesiae*, and *Prediscosphaera cretacea*), each of which has an average abundance of more than 10%. A set of nine secondary taxa are characterized by having average values of more than 2% or a maximum occurrence of more than 10%. The remaining 130 minor taxa have averages less than 2% and never occur at abundances more than 10%. Many of the major taxa exhibit significant differences in relative abundance between the onshore sites and the offshore sites. Several of these major taxa also exhibited strong paleobiogeographic preferences during the late Maastrichtian.

[15] *Micula decussata* was more abundant in high latitudes than low latitudes in the Maastrichtian [*Bukry*, 1973; *Wind*, 1979; *Wise*, 1983; *Pospichal and Wise*, 1990; *Watkins*, 1992]. It occurs with an average of 14.2% in the sample set, and is characterized by a large range of 3–46%. It is clearly more abundant in the onshore samples (average 17.4%) than in the offshore samples (average 8.6%) (Figure 3a). The onshore average is skewed by the presence of samples with high abundances (30–46%), but the two distributions are statistically different ($F = 74.4$, $p = 4.9 \times 10^{-15}$).

[16] *Watznaueria barnesiae* is nearly ubiquitous in Cretaceous assemblages with the exception of its distinctive absence in both northern [*Bukry*, 1973] and southern [*Wind*, 1979; *Watkins et al.*, 1996] high latitudes during parts of the Maastrichtian. In lower latitudes, it became significantly more abundant toward the equator, where it made up more than 20% of the total nannofossil assemblage [*Thierstein*, 1981]. *Watkins et al.* [1996] documented an abundance decline of *W. barnesiae* during the Maastrichtian in the Southern Ocean, which they attributed to the formation of a distinctive (cooler) surface water mass. A similar decline was documented by *Bergen and Sikora* [1999] for the Norwegian North Sea chalks, and was attributed to an overall Late Cretaceous cooling. There is clear separation between the onshore and offshore sets for this species (Figure 3b). The onshore assemblages have an average of 6.2%, whereas the offshore assemblages average 18.8%. The maximum value for the offshore assemblages is 30%, whereas it is only 16% in the onshore assemblages. The onshore and offshore assemblages are significantly different ($F = 400.3$, $p = 4.3 \times 10^{-46}$).

[17] The third primary species, *Prediscosphaera cretacea*, has an equivocal paleobiogeographic record for the Maastrichtian. *Wind* [1979] noted the high abundances of *P. cretacea* from the Falkland Plateau region and suggested a cool water affinity for the species. *Thierstein* [1981] noted that the species exhibited no clear pattern of distribution, as is clear from the presence of high abundances (>10%) associated with temperate latitudes in the North Atlantic and equatorial latitudes in the Pacific. He noted that the distribution pattern appeared to be influenced by closed sum effects of the dominant taxa including *W. barnesiae* and *M. decussata*. Subsequent examination of Southern Ocean assemblages from the Falkland Plateau by *Wise* [1983], Maud Rise by *Pospichal and Wise* [1990], and the Kerguelen Plateau by *Watkins* [1992] suggested elevated abundances at higher southern latitudes. In the present study, there is no obvious abundance trend, as there is no strong statistical difference between the onshore and offshore

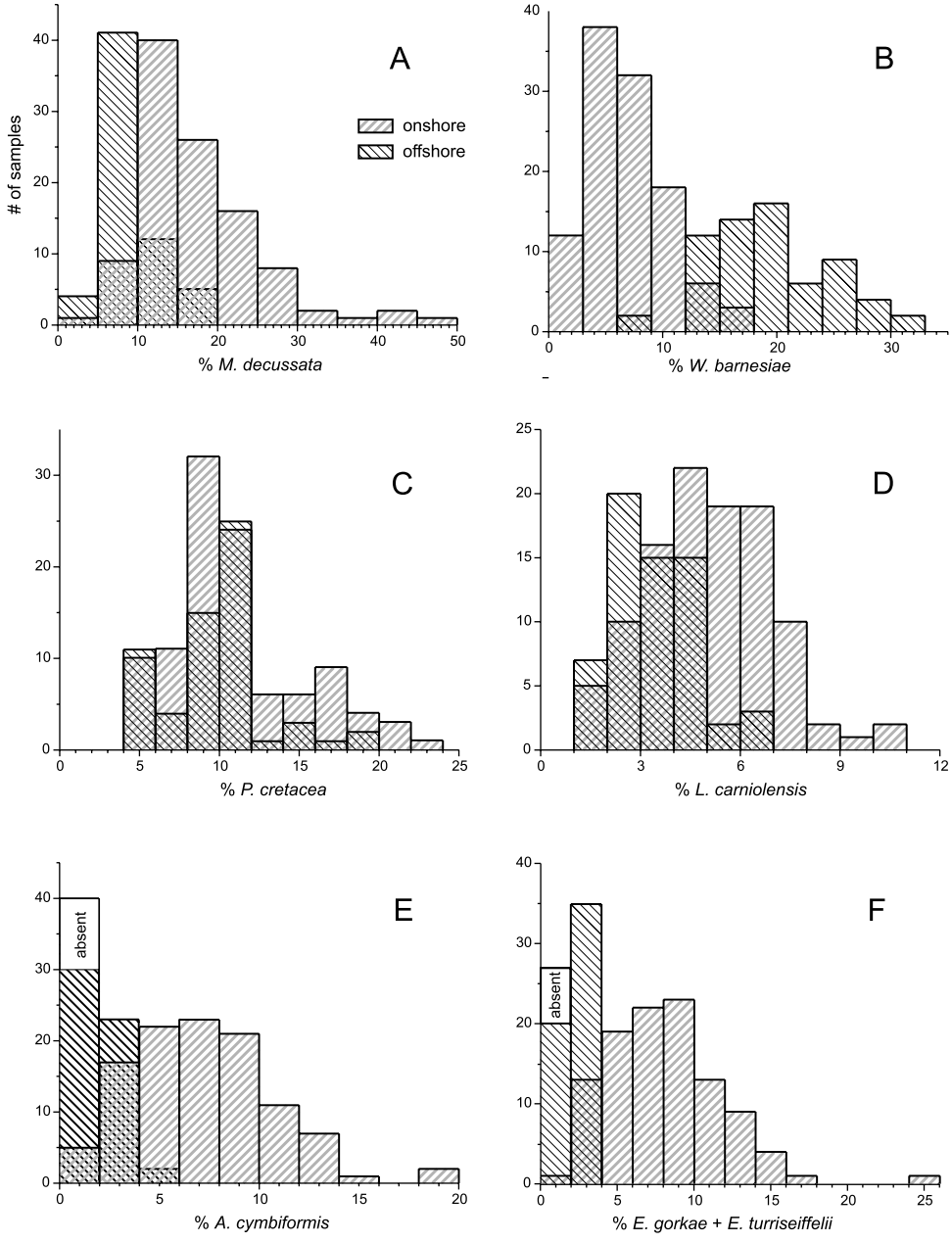

Figure 3. Histograms of major taxa illustrating the distributions of offshore and onshore data sets: (a) *M. decussata*, (b) *W. barnesiae*, (c) *P. cretacea*, (d) *L. carniolensis*, (e) *A. cymbiformis*, and (f) *E. gorkae* and *E. turriseiffelii*.

sets (F = 3.9, p = 0.05). Both the means and ranges of the sets are comparable (Table 1), and the two sets have similar distributions (Figure 3c).

[18] Several of the secondary major taxa exhibit significant differences in the onshore and offshore distributions. The clearest examples of this phenomenon are *Arkhangelskiella cymbiformis* and the eiffellithids (described below). In other cases, the lower abundances of the secondary major taxa make it difficult to identify a clear pattern of occurrence except by purely statistical means. As an example, *Lithraphidites carniolensis* has an equivocal distribution pattern graphically, in which the offshore samples fit entirely within the field defined by the onshore samples (Figure 3d). Analysis of variance indicates a strong separation of these distribution means (F = 30.2, p = 1.4×10^{-7}), however, indicating the preference of this species for onshore conditions. Similar distribution patterns exist for *Stradneria crenulata* and *Cribrosphaerella ehrenbergii*, although both of these species are more abundant in offshore localities (Table 1). The three other secondary major taxa (*Prediscosphaera stoverii*, *Placozygus spiralis*, and *Discorhabdus ignotus*) show no significant onshore-offshore distribution pattern (Table 1).

[19] *Arkhangelskiella cymbiformis* had a well-documented preference for high latitudes in the Maastrich-

Table 1. Statistics for Important Taxa, Including Mean and Range for All Samples (Total), *F* Statistic, Probability (p) That Onshore and Offshore Set Are the Same Distribution From ANOVA, and Mean and Range for Onshore and Offshore Sets

	Total		ANOVA[a]		Onshore		Offshore	
Spcies	Mean, %	Range, %	F	p	Mean, %	Range, %	Mean, %	Range, %
M. decussata	14.2	3–46	74.4	4.9×10^{-7}	17.4	4–46	2.8	1–7
W. barnesiae	10.9	1–30	400.3	4.3×10^{-46}	6.2	1–16	18.8	8–30
P. cretacea	10.4	4–24	3.9	0.05	10.8	4–24	9.6	4–19
A. cymbiformis	4.6	0–18	30.2	1.4×10^{-7}	6.6	1–18	1.3	0–5
L. carniolensis	4.0	1–10	30.2	1.4×10^{-7}	4.6	1–10	2.9	1–6
C. ehrenbergii	3.0	0–9	14.3	2.2×10^{-4}	2.2	0–9	4.5	2–8
P. stoveri	3.0	0–14	1.7	0.02	3.1	0–11	2.6	1–14
S. crenulata	2.8	1–10	60.4	7.6×10^{-13}	2.2	1–6	3.8	1–10
E. turriseiffelii	2.7	0–11	74.0	5.7×10^{-15}	3.5	0–11	1.3	0–3
E. gorkae	2.7	0–19	90.9	1.9×10^{-17}	4.0	0–19	0.3	0–1
P. spiralis	2.2	0–8	2.7	0.10	1.4	0–4	3.5	1–8
D. ignotus	1.8	0–11	3.4	0.07	2.0	0–11	1.5	0–6

[a]ANOVA is analysis of variance.

tian that was manifested by markedly higher abundances relative to the temperate and tropical regions [*Bukry*, 1973; *Wind*, 1979; *Thierstein*, 1981; *Pospichal and Wise*, 1990; *Watkins*, 1992]. It is present at all onshore sites at abundances of at least 1% and up to 18%, with an average of 6.6%. It is absent in 16% (10/62) of the offshore samples, has a maximum value of only 5%, and an average of 1.3%. The onshore and offshore sample sets are significantly different ($F = 30.2$, $p = 1.4 \times 10^{-7}$) with the onshore assemblages strongly enriched relative to the offshore assemblages (Figure 3e). *Kamptnerius magnificus*, also a member of the Family Arkhangelskiellaceae, exhibits a similar separation of onshore and offshore distributions ($F = 35.0$, $p = 1.8 \times 10^{-8}$), although it is never as abundant as *A. cymbiformis*.

[20] *Eiffellithus turriseiffelii* has been shown to have higher relative abundances in high latitudes than low latitudes in the Maastrichtian [*Wise and Wind*, 1977; *Wind*, 1979; *Thierstein*, 1981; *Wise*, 1983; *Pospichal and Wise*, 1990; *Watkins*, 1992].The two sample sets are statistically different ($F = 74.0$; $p = 5.7 \times 10^{-15}$), with higher abundances in the onshore samples (average 3.5%, maximum 11%) as opposed to the offshore samples (average 1.3%, maximum 3.0%). Its sister species, *E. gorkae*, exhibits a similar behavior, with a clear separation of the onshore and offshore distributions ($F = 90.9$, $p = 1.9 \times 10^{-17}$). Combining these two species, as was almost certainly done in the earlier paleobiogeographic work cited above, yields the distributions illustrated in Figure 3f.

[21] Several of the minor taxa are known to have been significantly more abundant at high latitudes than low latitudes in the Maastrichtian. The low abundance and frequent absence (in the counts of 450) of these taxa in the current data set render statistical determinations of their distribution patterns questionable. There are a few of these taxa that warrant analysis, however, because of their well-documented paleobiogeographic patterns during the Maastrichtian. For example, the genus *Ceratolithoides* showed a strong preference for low latitudes during the Maastrichtian, as demonstrated by its abundance pattern and its absence from polar regions [*Wise and Wind*, 1977; *Thierstein*, 1981; *Watkins*, 1992; *Lees*, 2002]. In the present study, *Ceratolithoides* spp. average 1.6% in the offshore assemblages and only 0.4% in the onshore assemblages. Analysis of variance indicates a clear separation of the sets into two distinct distributions ($F = 112.1$, $p = 2.4 \times 10^{-20}$).

[22] In a similar manner, two important biostratigraphic indicators for the latest Maastrichtian, *Nephrolithus frequens* and *Micula murus*, had distinctly different paleobiogeographic preferences [*Worsley and Martini*, 1970]. The former preferred high latitudes and had a distinctly diachronous first occurrence linked to global temperature change in middle paleolatitudes [*Thierstein*, 1976, 1981; *Pospichal and Wise*, 1990; *Watkins*, 1992; *Watkins et al.*, 1996]. In the present study, *N. frequens* is absent from all offshore samples (28) from zone 26, while it is present in 30% (10/33) of the nearshore zone 26 samples with abundances as high as 2.4% of the assemblage. *Micula murus* preferred low latitudes and was completely absent from the high-latitude areas of the latest Maastrichtian [*Worsley and Martini*, 1970; *Thierstein*, 1976, 1981; *Watkins et al.*,

Table 2. Published Paleotemperature Preferences of Selected Species and Their Preferences for Either Onshore or Offshore in This Study

Species	Published Paleolatitude Preference	References[a]	Preference This Study
A. octoradiata	cool	7, 8	onshore
A. cymbiformis	cool	2, 4, 6, 7, 9	onshore
E. turriseiffelii	cool	4, 6, 7, 9, 10, 11	onshore
M. decussata	cool	2, 4, 7, 9, 11	onshore
N. frequens	cool	4, 5, 6, 7, 8, 12	onshore
P. cretacea	cool?	4, 6, 7, 9, 11	indeterminate
Ceratolithoides spp.	warm	3, 6, 7, 10	offshore
M. murus	warm	5, 6, 8, 12	offshore
W. barnesiae	warm	1, 2, 6, 8, 9	offshore

[a]References include 1, *Bergen and Sikora* [1999]; 2, *Bukry* [1973]; 3, *Lees* [2002]; 4, *Pospichal and Wise* [1990]; 5, *Thierstein* [1976]; 6, *Thierstein* [1981]; 7, *Watkins* [1992]; 8, *Watkins et al.* [1996]; 9, *Wind* [1979]; 10, *Wise and Wind* [1977]; 11, *Wise* [1983]; and 12, *Worsley and Martini* [1970].

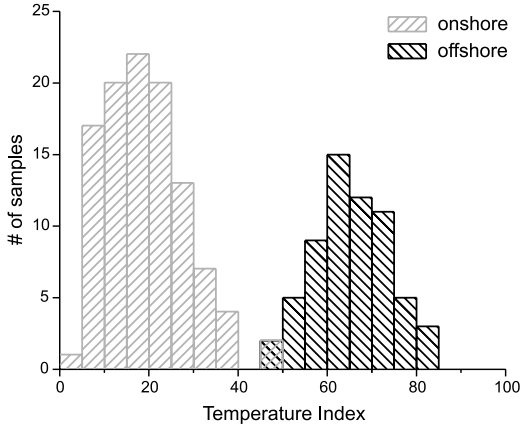

Figure 4. Histogram of temperature index values illustrating the distributions of offshore and onshore data sets.

1996]. This species is present in all (28) of the offshore zone 26 samples, with abundances as high as 4%, whereas it is present in less than half (16/33) of the onshore zone 26 samples and is never more than 1.6% in abundance. The distribution of these two species is corroborating evidence of warmer offshore and cooler nearshore surface waters.

[23] The paleolatitudinal preferences of the species discussed above are summarized in Table 2. Note that species with a preferred distribution in high paleolatitudes in published studies are more abundant in onshore samples in this study. Conversely, those species documented as low-latitude species in published studies exhibit higher abundances in offshore samples. The only exception is *P. cretacea*, whose published preference is uncertain, and distribution in this study is indeterminate.

[24] As discussed above, the published literature indicates that several important Maastrichtian taxa had clear preferences for high or low latitudes. The marked association of these species abundance patterns with paleolatitude strongly indicates that their distributions were related to latitudinal temperature gradients. A temperature index was constructed using the relative abundances of those taxa identified in the literature as having the most reliable paleogeographic preferences. The temperature index (TI) was calculated as follows:

$$\mathrm{TI} = [\text{percent warm taxa}/(\text{percent warm taxa} + \text{percent cool taxa})] \times 100$$

Warm taxa consist of *W. barnesiae*, *Ceratolithoides* spp., and *Micula murus* and cool taxa include *A. octoradiata*, *A. cymbiformis*, *E. turriseiffelii*, *M. decussata*, and *N. frequens*. Analysis of variance of the TI values grouped according to location indicates a strong separation of the distributions (F = 1078) with a probability that the two sets are the same of a diminishingly small 1.6×10^{-74}. There is only slight overlap of the two sets (Figure 4) and the means are clearly different.

[25] Principal component analysis (PCA) was performed on the variance-covariance matrix including all taxa (56 species) that made up at least 2% in at least one sample. The first principal component (PCA1) has an eigenvalue of 0.10, representing 47.1% of the total variance. *Watznaueria barnesiae* has the highest component loading (0.064) for PCA1 with a correlation of 0.913 to PCA1. A second group of species have strong positive correlations for PCA1 including the major taxa *Cribrosphaerella ehrenbergii, Placozygus spiralis*, and *Stradneria crenulata* (Table 3). There is a diverse group of taxa that share significant negative correlations with PCA1 including the dominant *Micula decussata*, *A. cymbiformis*, the two eiffellithids (*E. gorkae* and *E. turriseiffelii*), *Ahmuellerella octoradiata*, *Chiastozygus antiquus*, and the calcareous dinoflagellates *Thoracosphaera* spp. All of the species above correlate to *W. barnesiae* (either positively or negatively) at a high confidence level ($p < 1 \times 10^{-9}$).

[26] The principle component scores of this factor for each sample, plotted in Figure 5, reveal a highly nonrandom distribution. All of the offshore Atlantic samples (DSDP Site 10 and ODP sites 1050 and 1052) have highly positive component scores, whereas all of the onshore samples have neutral to strongly negative component values, indicating a strongly expressed difference between the nearshore and offshore sites in the study area. Analysis of variance indicates a clear separation of these two sets at a high degree of confidence (F = 708, $p = 8.0 \times 10^{-62}$). The clear division of principle component values into a nearshore and oceanic group indicate some environmental component was the most significant factor in determining the distribution of coccolithophorids in the study area. The temperature index was compared directly to PCA1 scores, yielding a correlation coefficient of 0.975 ($p < 1 \times 10^{-99}$) that supports strongly the hypothesis that PCA1 is an expression of paleotemperature.

5. Summary and Conclusions

[27] Analyses of variance of the major species indicate that most have significantly higher abundances in either

Table 3. Significant Species and Their Correlations to PCA 1

Species	Correlation to PCA1[a]
Watznaueria barnesiae	0.913
Microrhabdulus decoratus	0.736
Placozygus spiralis	0.708
Corollithion madagaskarensis	0.703
Cylindralithus spp.	0.693
Ceratolithoides indiensis	0.627
Cribrocorona gallica	0.605
Cribrosphaerella ehrenbergii	0.600
Semihololithus sp.	0.580
Stradneria crenulata	0.580
Biscutum zulloi	0.577
Tranolithus minimus	0.573
Vagalipilla aachena	−0.505
Ahmuellerella octoradiata	−0.526
Chiastozygus antiquus	−0.530
Eiffellithus turriseiffelii	−0.552
Angulofenestrellithus snyderi	−0.579
Thoracosphaera spp.	−0.586
Eiffellithus gorkae	−0.618
Arkhangelskiella cymbiformis	−0.688
Micula decussata	−0.747

[a]PCA 1, principal component analysis 1.

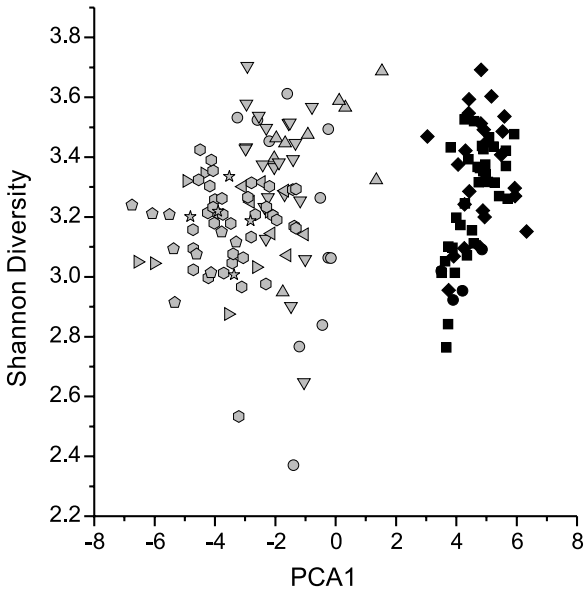

Figure 5. Distribution of principal component analysis 1 (PCA1) values relative to Shannon diversity index for the offshore data set (solid symbols) and onshore data set (shaded symbols).

the onshore or offshore assemblages (Table 1 and Figure 3). Three of the five major species that exhibit higher abundances in onshore assemblages (*M. decussata*, *A. cymbiformis*, and *E. turriseiffelii*) are known to have preferred high-latitude localities during the late Maastrichtian. The fourth major species, *E. gorkae*, was probably included within the taxonomic concept of *E. turriseiffelii* by earlier workers, while the fifth (*L. carniolensis*) had a paleogeographic distribution that is not well documented. One of the three major taxa that are more abundant in offshore assemblages (*W. barnesiae*) has a well-documented preference for low-latitude localities in the upper Maastrichtian, while the other two (*C. ehrenbergii* and *S. crenulata*) have distributions that are equivocal. The apparent preferences of high-latitude species for onshore localities and low-latitude species for offshore localities are corroborated by the distributions of *Ceratolithoides* spp., *M. murus*, and *N. frequens*.

[28] Calculation of a temperature index by using the relative abundances of taxa known from the literature to have distinctive paleolatitudinal preferences yields a similar distribution, with a strong preference of high-latitude taxa for onshore localities and low-latitude taxa for offshore localities (Figure 4). Assuming that the paleolatitudinal preferences of the chosen species were controlled by latitudinal temperature gradients during the late Maastrichtian, it is clear that the offshore localities were significantly warmer than the onshore localities.

[29] Eigenvector extraction by principal components analysis indicates that the dominant factor in the data matrix is an idealized end-member assemblage with strong positive loading for *W. barnesiae* and negative loadings for *A. cymbiformis* and the eiffelilithids (Table 3). Results from published paleolatitudinal studies are consistent with a low-latitude signal for positive loadings and a high-latitude signal for negative loadings. Plotting the component scores for individual samples results in a clear separation of strongly positive scores for offshore samples from the negative to neutral scores for onshore samples (Figure 5).

[30] The clear separation of the onshore and offshore sets by principal components and thermal index analysis is in sharp contrast with the results of Shannon diversity analysis. As is illustrated in Figure 5, the diversity values from both sets varies widely between 3.8 and <2.7. This indicates that assemblages from both samples sets inhabited surface waters that varied significantly in terms of surface fertility and productivity. The complete lack of power to resolve the two sample sets by Shannon diversity, as opposed to the clear separation of these sets by principal components, indicates that the strong thermal contrast persisted between the sets despite significant changes in the surface water fertility and paleocommunity stability in both sets.

[31] The three analytical methods of the calcareous nannofossil data (analysis of variance of major species distribution, calculation of a temperature index based on published paleobiogeographical inferences, and principal components analysis) yield the same result. There is a clear division of the sample set into an onshore South Carolina Coastal Plain set and an offshore Atlantic set. In all cases, species known to have preferred high latitudes (=cool surface waters) during the late Maastrichtian are more abundant in the onshore assemblages, while those known to have preferred low latitudes (warm surface waters) are more abundant in offshore samples. These analyses indicate strongly that the offshore localities were characterized by significantly warmer surface water temperatures than the onshore localities during the late Maastrichtian. This is precisely the thermal structure that would be imposed by the presence of a stable, persistent western boundary current and thus this study supports the contention that a Gulf Stream current was active during the late Maastrichtian across the Blake Plateau.

[32] *Frank and Arthur* [1999] postulated that a major reorganization of the oceanic circulation patterns occurred near the early/late Maastrichtian boundary. This reorganization resulted in the development of an oceanic thermohaline circulation system that was similar in many ways to the modern system. Our evidence of a late Maastrichtian Gulf Stream fits well with the concept of a relatively modern thermohaline system by indicating that the western boundary current of the North Atlantic Gyre was actively flowing at this time.

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