

## Maastrichtian North Atlantic warming, increasing stratification, and foraminiferal paleobiology at three timescales

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[1] Analysis of 944 single specimens of three species of late Maastrichtian planktonic foraminifera (*Racemiguembelina fructicosa*, *Contusotruncana contusa*, and *Rugoglobigerina rugosa*) from 38 samples spanning the last 3 Myr of the Cretaceous shows consistent isotopic trends through time, consistent isotopic differences among taxa, and high within-sample isotopic variability throughout. Within-sample variability does not change systematically through time for any taxon, but average  $\delta^{18}\text{O}$  values decrease by  $\sim 1.5\text{‰}$ , and average  $\delta^{13}\text{C}$  values diverge up section. Comparing taxa, average  $\delta^{18}\text{O}$  values are similar within most samples, but average  $\delta^{13}\text{C}$  values generally decrease from *R. fructicosa* to *R. rugosa* to *C. contusa*. In addition, the within-sample variability of individual  $\delta^{13}\text{C}$  measurements is larger for *R. fructicosa* than for either *C. contusa* or *R. rugosa*, an observation which is consistent with a photosymbiotic habitat for *R. fructicosa*. In terms of Maastrichtian paleoceanography the negative  $\delta^{18}\text{O}$  trend of  $\sim 1.5\text{‰}$  corresponds to a temperature increase of  $\sim 6^\circ\text{C}$ , and the divergence of  $\delta^{13}\text{C}$  values up section suggests an increasingly stratified water column in the western Atlantic through the late Maastrichtian. We suggest that these trends are best explained by increasing import of South Atlantic waters into the North Atlantic and an intensification of the Northern Hemisphere polar front.

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### 1. Introduction

[2] The Cretaceous represents one of the warmest intervals in Earth's history, but conditions were not uniformly warm across the period. It consisted of intervals of warming and cooling with associated paleoclimatic and paleoceanographic responses at different timescales. This study investigates  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  variability of three species of Cretaceous planktic foraminifera. We measured 944 individual specimens of *Racemiguembelina fructicosa*, *Contusotruncana contusa*, and *Rugoglobigerina rugosa* from 38 samples from Ocean Drilling Program Site 1050C (Blake Nose, western North Atlantic) (Figure 1). The 38 samples span the last 3 Myr of the Cretaceous, and the data capture variability at three distinct timescales: within sample ( $\sim 10^2$  years), across Milankovitch-scale cycles ( $\sim 10^4$  years), and across the last half of the Maastrichtian ( $\sim 10^6$  years). Some of the characteristics that make Blake Nose an excellent site to study Cretaceous paleoceanography and foraminiferal paleobiology are the abundance of foraminifera, the very good to excellent preservation with only minimal evidence of diagenetic alteration [Norris *et al.*, 1998; MacLeod *et al.*, 2001; MacLeod and Huber, 2001; Rudnicki *et al.*,

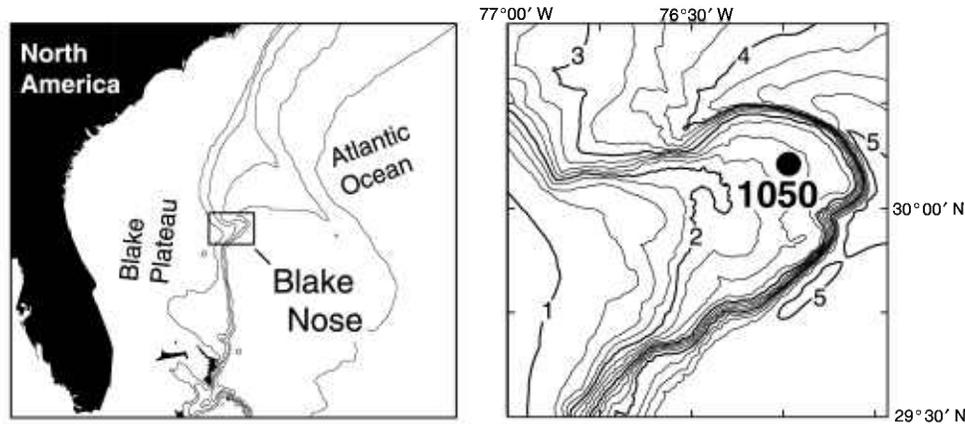
2001], and the previous documentation of isotopic signals on both Milankovitch timescales [MacLeod *et al.*, 2001] and through the Maastrichtian [e.g., Frank and Arthur, 1999; MacLeod and Huber, 2001; MacLeod *et al.*, 2005].

[3] The three foraminiferal taxa studied were chosen because their large size allows easy analysis of individual specimens. In addition, the three species are thought to have lived in separate ecological niches in the water column. *R. fructicosa* has been proposed as a photosymbiotic taxon, *R. rugosa* as a surface mixed dweller, and *C. contusa* as a relatively deep dweller [Malmgren, 1991; D'Hondt and Arthur, 1995; D'Hondt and Zachos, 1998; Kucera and Malmgren, 1998; Nederbragt, 1998; Houston and Huber, 1998; Houston *et al.*, 1999; Premoli-Silva and Sliter, 1999; MacLeod *et al.*, 2001; Abramovich *et al.*, 2003]. Thus our analysis should allow us to track changes in different parts of the planktonic realm on the three timescales targeted.

[4] Each  $\sim 5\text{ cm}^3$  bulk sample collected spans a stratigraphic interval that represents several hundred years on the basis of estimated average sedimentation rates [e.g., Norris *et al.*, 1998; MacLeod *et al.*, 2001, 2005]. An adult foraminiferal test represents about 1 month of growth [Bijma *et al.*, 1990]. Thus variability in values among specimens from the same sample should reflect a combination of the breadth of conditions within the niche of each taxon as well as intra-annual and interannual variability at the  $10^2$  year scale. Characterizing variability on this timescale will allow us to examine planktonic foraminifer paleobiology and to search for systematic changes in short-

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**Figure 1.** Location of Blake Nose and ODP Hole 1050C. (left) Position relative to southeastern North America. (right) Topographic detail of Blake Nose with depth contours labeled in km (modified from Klaus *et al.* [2000]).

term variables (e.g., increasing or decreasing seasonality) that would show up as trends in within-sample standard deviation.

[5] Milankovitch-scale cyclicity is observed within the pelagic portions of the Maastrichtian Blake Nose as color and magnetic susceptibility variations [Norris *et al.*, 1998; MacLeod *et al.*, 2001]. The cycles are thought to be an expression of the  $\sim 21$  kyr precessional cycle [MacLeod *et al.*, 2001]. Lighter intervals were apparently deposited during times of relatively high productivity and relatively cool temperatures, and darker sediments seem to represent deposition during low productivity and warm/less saline surface waters [MacLeod *et al.*, 2001]. Data across low-amplitude cycles in a younger interval show similar but subdued trends [Isaza *et al.*, 2003]. Our new analyses test whether cyclic isotopic variations occur in the three taxa studied and, through characterization of within-sample variability, whether changes in seasonality or surface water gradients were part of the expression of orbital forced cyclicity.

[6] On geological timescales the Maastrichtian has been characterized as a time of global cooling between warmer climates earlier in the Late Cretaceous and in the early Eocene. Well-documented cooling trends and other global changes related to paleobiology and reorganization of water circulation have been observed in the Maastrichtian [e.g., MacLeod and Huber, 1996; Barrera and Savin, 1999; Frank and Arthur, 1999; MacLeod and Huber, 2001; Frank *et al.*, 2005]. However, cooling during the Maastrichtian is best documented for the Southern Hemisphere and tropical Pacific [e.g., D'Hondt and Lindinger, 1994; Barrera and Savin, 1999; Frank and Arthur, 1999]. A recent compilation of paleotemperature data spanning the Maastrichtian summarized these patterns and, with the addition of new data from Blake Nose, concluded that there was warming of up to  $6^{\circ}\text{C}$  throughout the North Atlantic region during the Maastrichtian “cooling” interval [MacLeod *et al.*, 2005]. This paper examines in detail the isotopic patterns of three planktic foraminifera during the North Atlantic warming trend. What makes this study different from previous work is the range of temporal scales being examined simulta-

neously through the analysis of many single individuals in multiple samples.

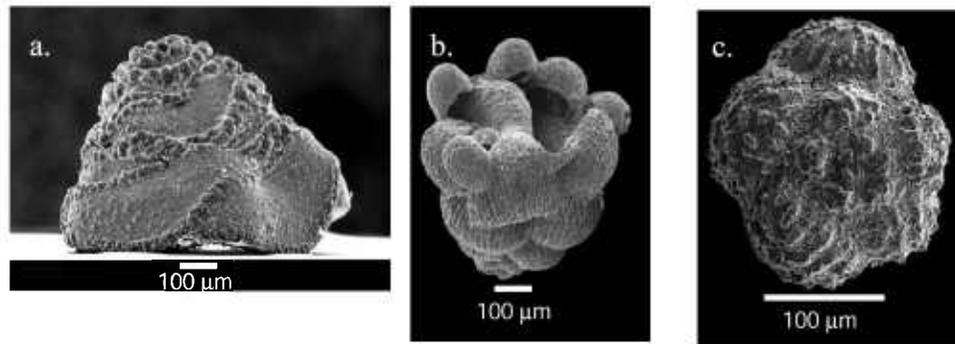
## 2. Material, Methods, and Location

### 2.1. Study Site

[7] Ocean Drilling Program (ODP) Site 1050, located at 2300 m water depth, is the second deepest of five sites drilled during ODP Leg 171B on the crest of Blake Nose (Figure 1), which is an eastward dipping and gently sloping topographic high that extends into the western Atlantic from Blake Plateau. On Blake Nose, Aptian-Albian shallow water carbonates are overlain by a sequence of Paleogene and Late Cretaceous pelagic sediments that are capped by a thin veneer of manganiferous sand and nodules [Norris *et al.*, 2001]. Maastrichtian and uppermost Campanian strata are represented in Hole 1050C by over 200 m of pelagic chalk and occasional slumped intervals [MacLeod *et al.*, 2000]. This sequence contains abundant, well-preserved foraminifera [Norris *et al.*, 1998; MacLeod *et al.*, 2000; Norris *et al.*, 2001; MacLeod and Huber, 2002]. During the Maastrichtian, Blake Nose was at tropical/subtropical latitude of  $\sim 30^{\circ}\text{N}$  near the northwestern edge of the Tethyan Seaway. Maastrichtian paleodepths are estimated at  $\sim 1.5$  km [Norris *et al.*, 1998].

### 2.2. Taxa Analyzed

[8] The species selected for this study, *Racemiguembelina fructifera* (Egger 1899), *Contusotruncana contusa* (Cushman 1926), and *Rugoglobigerina rugosa* (Plummer 1926) (Figure 2), have different ecological and biological characteristics that allow simultaneous examination of trends in different planktic niches. The multiserial taxon *R. fructifera* has been interpreted as having harbored photosymbionts, as evidenced by its high  $\delta^{13}\text{C}$  values and  $\delta^{13}\text{C}$ /size-related trends [D'Hondt and Arthur, 1995; D'Hondt and Zachos, 1998; Houston and Huber, 1998; Houston *et al.*, 1999; Abramovich *et al.*, 2003]. Lack of such  $\delta^{13}\text{C}$ /size correlations suggests that *C. contusa* and *R. rugosa* were most likely asymbiotic [D'Hondt and Zachos, 1998; Kucera and



**Figure 2.** Species analyzed. (a) *Contusotruncana contusa* 1050C 16R-2 120 cm (Cushman 1926). (b) *Racemiguembelina fructicosa* 1050C 13R-5 55cm (Egger 1899). (c) *Rugoglobigerina rugosa* 1050C 11R-1 75cm (Plummer 1926).

Malmgren, 1998; Premoli-Silva and Sliter, 1999]. Similar to modern photosymbiotic foraminifera [Hemleben et al., 1989], *R. fructicosa* was most abundant in subtropical to high middle latitude open ocean settings. Relatively low  $\delta^{18}\text{O}$  isotopic values suggest that *R. fructicosa* usually inhabited the surface/near-surface mixed layer [Malmgren, 1991; D'Hondt and Zachos, 1998; Abramovich et al., 2003]. On the basis of relatively low  $\delta^{13}\text{C}$  and high  $\delta^{18}\text{O}$  isotopic signatures, *C. contusa* is thought to have been an oligotrophic deep surface dweller [Kucera and Malmgren, 1998]. Paleobiogeographic distributions, generally low  $\delta^{18}\text{O}$  values, and high  $\delta^{13}\text{C}$  values suggest that *R. rugosa* inhabited the mixed layer at mid to low latitudes [Malmgren, 1991; D'Hondt and Arthur, 1995; Nederbragt, 1998; Barrera and Savin, 1999; MacLeod et al., 2001; MacLeod and Huber, 2001; Abramovich et al., 2003].

### 2.3. Sample Preparation

[9] Specimens were collected from 38 samples from ODP Hole 1050C, cores 11–16 (408–455 m below seafloor), that span the *R. fructicosa* and *Abathomphalus mayaroensis* foraminiferal biozones and thus represent approximately the last 3 Myr of the Cretaceous [Premoli-Silva and Sliter, 1999]. Bulk samples were dried (<50°C), weighed, and disaggregated using kerosene and distilled water before being washed on a 63  $\mu\text{m}$  screen. The wash water with the <63  $\mu\text{m}$  fraction was collected, and sediments were allowed to settle before decanting. Coarse and fine fractions were then dried, weighed, and saved.

[10] Up to 20 of the best preserved specimens (no signs of overgrowth, translucent, consistent morphology) of *R. fructicosa*, *C. contusa*, and *R. rugosa* were picked from the >250  $\mu\text{m}$  fraction (Figure 2). In all the samples the largest well-preserved specimens were picked to allow single-specimen analysis and to maximize the probability of selecting only adults. Picked individuals were sonicated in distilled water and methanol and dried in an oven at 50°C. Any specimens with adhering matrix or discoloration were rejected, and 10 specimens per sample (if present) were selected for single-specimen isotopic measurements.

### 2.4. Stable Isotope Analysis

[11] Each specimen was weighed, loaded into an individual reaction vessel, and reacted with three drops of phos-

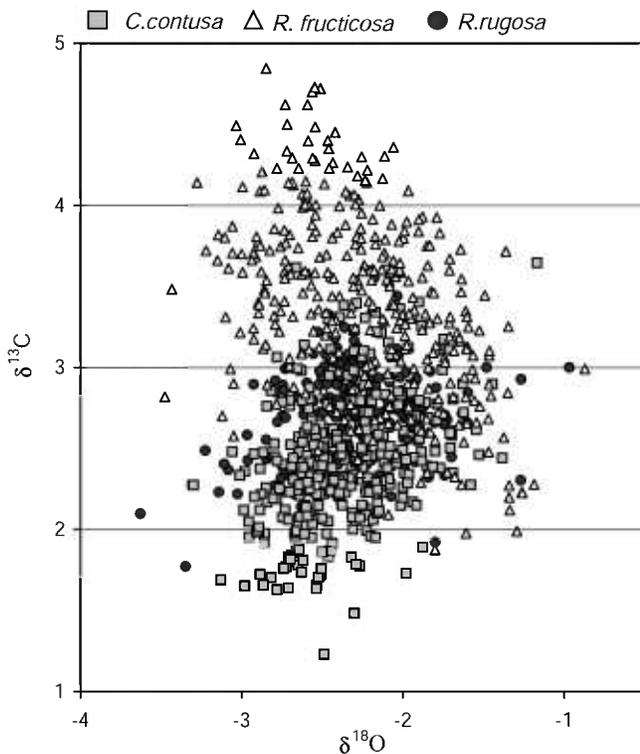
phoric acid at 70°C in a Kiel III carbonate device. The  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values of the resultant  $\text{CO}_2$  were measured online in a Thermo Finnegan Delta Plus mass spectrometer in the Biogeochemistry Isotope Laboratory at the University of Missouri. Results are expressed in  $\delta$  notation relative to the Vienna Pee Dee belemnite standard (VPDB). The mass spectrometer was calibrated for each run on the basis of the average of multiple analysis of NBS-19 standard. The precision of the instrument during the duration of this study was <0.03‰ and <0.05‰ for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ , respectively (1 $\sigma$  standard deviation).

### 3. Results

[12] The 944 isotopic measurements (Figure 3 and Tables S1 and S2 in the auxiliary material<sup>1</sup>) of the three taxa analyzed define broad, overlapping fields in  $\delta^{13}\text{C}/\delta^{18}\text{O}$  space. In general, the taxa studied show similar  $\delta^{18}\text{O}$  values and a decrease in  $\delta^{13}\text{C}$  values from *R. fructicosa* to *R. rugosa* to *C. contusa*. Test mass was used to quantify size, and there is no apparent correlation between this measure and  $\delta^{18}\text{O}$  values or  $\delta^{13}\text{C}$  values in *R. fructicosa* or *R. rugosa* either within samples or in the entire data set (Figures 4 and 5 and Tables S1 and S2). *C. contusa* shows a negative correlation between test mass and both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  (Figure 5), but this correlation is the result of a trend to larger size and lower  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values in this taxon through time (Figure 4); there is no corresponding correlation between size and isotopic values within specimens of *C. contusa* from the same sample.

[13] *R. fructicosa* and *R. rugosa* also show a decrease in  $\delta^{18}\text{O}$  values up section. *R. fructicosa* shows no temporal trend in  $\delta^{13}\text{C}$  values, but there is a slight increase in the average  $\delta^{13}\text{C}$  values of *R. fructicosa*. That is, all taxa show decrease in  $\delta^{18}\text{O}$  values, and there is a divergence in  $\delta^{13}\text{C}$  values through time (Figures 4 and 5). In addition, high within-sample variability is observed in all three species (up to 2.4‰ spread in  $\delta^{13}\text{C}$  values is observed within some samples for *R. fructicosa*). Finally, Milankovitch cyclicity can only be resolved in the  $\delta^{18}\text{O}$  signatures from

<sup>1</sup>Auxiliary material is available at <ftp://ftp.agu.org/apend/pa/2004pa001130>.



**Figure 3.** Plot of  $\delta^{18}\text{O}$  values versus  $\delta^{13}\text{C}$  values for all specimens analyzed. Notice the lack of correlation between these variables for any taxon and the particularly large range in  $\delta^{13}\text{C}$  values of *R. fructicosa*.

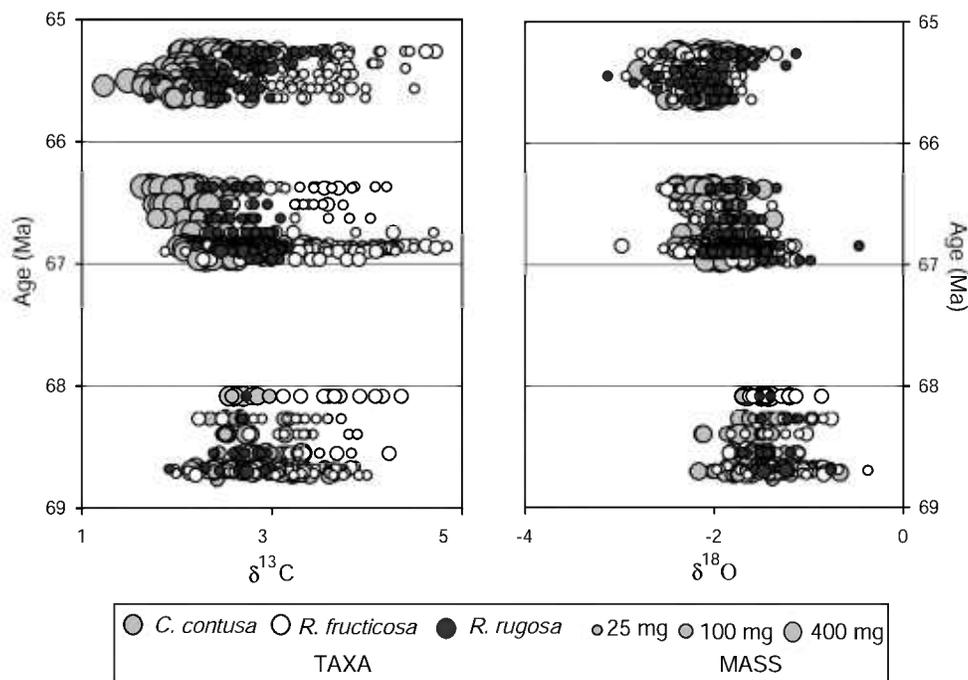
16R-2 samples in all three species but not in their  $\delta^{13}\text{C}$  values (Figure 6).

### 3.1. Within-Sample Variability

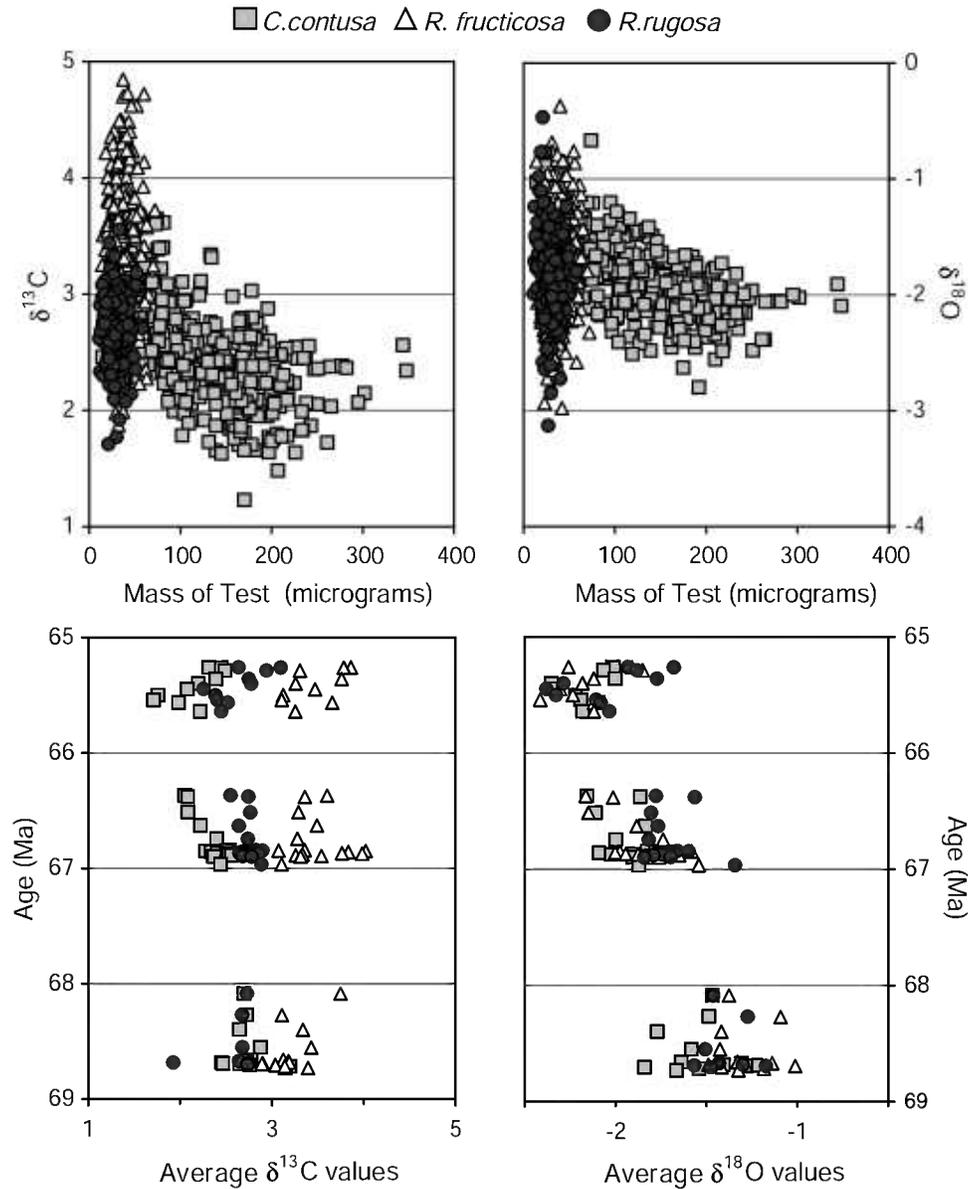
[14] The spread of data plotted in Figure 3 is largely the result of high within-sample variability for all species and taxa. For example, the range in  $\delta^{13}\text{C}$  of 2.4‰ for the 10 specimens of *R. fructicosa* measured from sample 13R-4, 75cm, is 74% of the total range exhibited by the 360 specimens of *R. fructicosa* (from 38 samples) analyzed. *R. fructicosa* shows the largest  $\delta^{13}\text{C}$  within-sample variability (average range is 1.5‰) and shows the highest average  $\delta^{13}\text{C}$  values (2.4‰). *R. rugosa* and *C. contusa* both present very similar  $\delta^{13}\text{C}$  average values (1.3‰) and within-sample variability (average range 0.5‰). A very similar within-sample  $\delta^{18}\text{O}$  range of  $\sim 1.5\text{‰}$  is observed for the three species. Any interspecies difference in average  $\delta^{18}\text{O}$  values is small relative to this within-sample variability. In subsequent discussion, within-sample variability is quantified as the standard deviation of the individual isotopic results for each taxon from each sample.

### 3.2. Milankovitch-Scale Variability

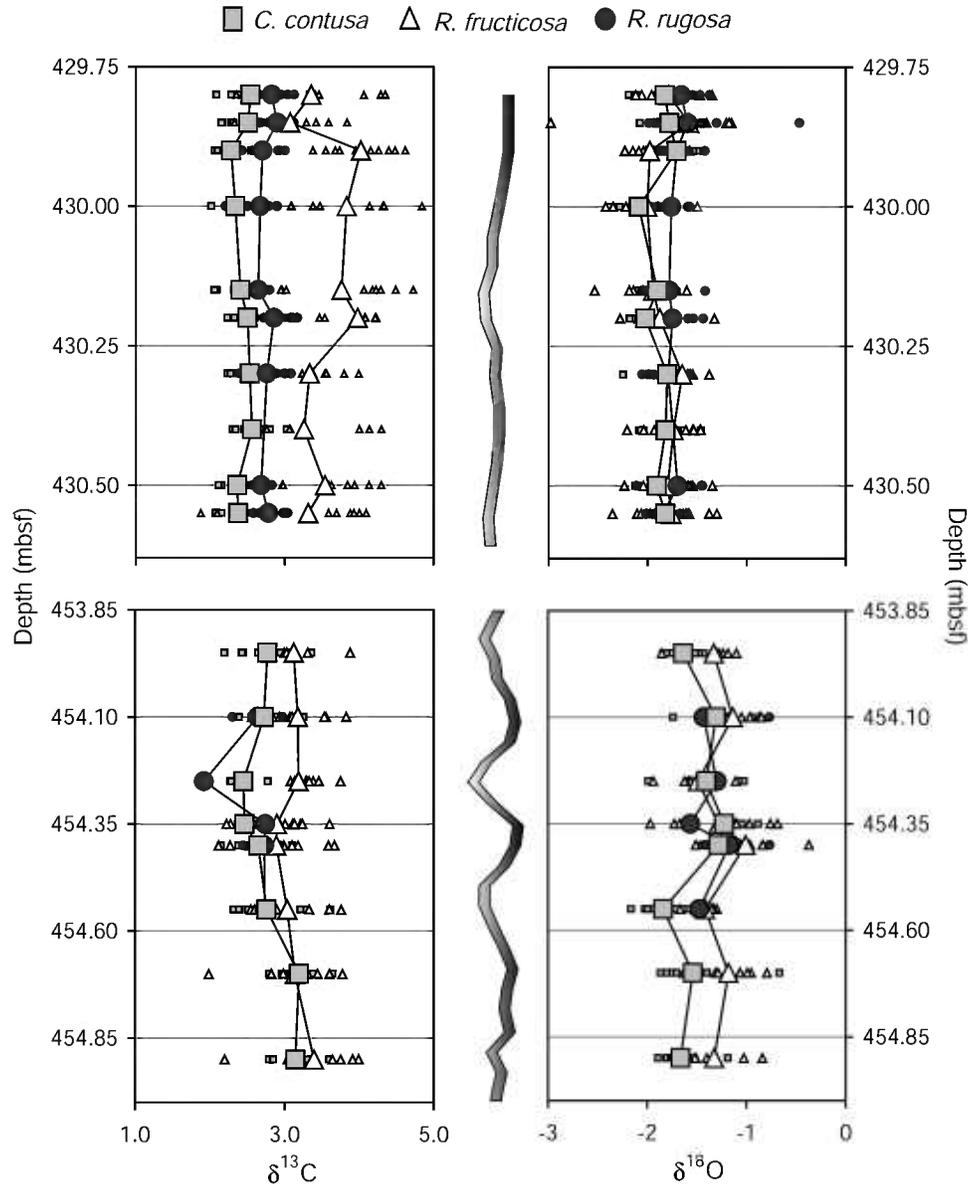
[15] Cyclic variations up to 0.6‰ and 0.8‰ for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ , respectively, have been reported for three other planktic taxa in some of these samples [MacLeod *et al.*, 2001; Isaza *et al.*, 2003]. Given the high degree of within-sample variability in isotopic values observed in this study, it is surprising that relatively small cyclic variations can be seen in any of the samples examined. However, average within-sample  $\delta^{18}\text{O}$  values for core section 16R-2 show cyclicity that is compara-



**Figure 4.** Stable isotopic (left)  $\delta^{13}\text{C}$  and (right)  $\delta^{18}\text{O}$  results for *C. contusa*, *R. fructicosa*, and *R. rugosa* plotted against age [MacLeod *et al.*, 2005]. *R. fructicosa* shows the highest within-sample variability as well as the highest  $\delta^{13}\text{C}$  values. Notice high but constant within-sample variability and long-term trends. Size of symbols scales directly with test mass.



**Figure 5.** (top) Stable isotopic results versus test mass. Neither *R. rugosa* nor *R. fructicosa* show a correlation between test mass and isotopic values either within samples or across all specimens. *C. contusa* does show correlation between test mass and both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values across all specimens but not within samples, and thus the correlation is interpreted as resulting from consistent temporal trends in all three variables rather than a size-related isotope effect. (bottom) Within-sample average  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values for *C. contusa*, *R. fructicosa*, and *R. rugosa* for each of the 38 samples studied plotted against age [MacLeod et al., 2005]. Among taxa, *C. contusa* tends to have the lowest average  $\delta^{13}\text{C}$  values, and *R. fructicosa* tends to have the highest, but there is no consistent ranking in  $\delta^{18}\text{O}$  values. Through the section, there is a negative excursion in  $\delta^{18}\text{O}$  values exhibited in all three taxa and a divergence in their average  $\delta^{13}\text{C}$  values.



**Figure 6.** Results for the three study taxa plotted against Milankovitch-scale cyclicity for (top) core section 13R-5 and (bottom) core section 16R-2. The shaded gray bar represents the magnitude of color variation across the cycles [MacLeod et al., 2001]. There is no apparent  $\delta^{13}\text{C}$  cyclicity in either interval or in  $\delta^{18}\text{O}$  for 13R-5. Cyclicity comparable to that found among other taxa is seen in  $\delta^{18}\text{O}$  values for 16R-2. Large symbols represent the average isotopic values of the single-specimen analysis (small symbols) within that sample.

ble to the cyclicity previously documented (Figure 6). No apparent cyclicity is observed in the  $\delta^{13}\text{C}$  data, in  $\delta^{18}\text{O}$  data from core section 13R-5, or for the within-sample variability for either  $\delta^{18}\text{O}$  or  $\delta^{13}\text{C}$  for any taxon.

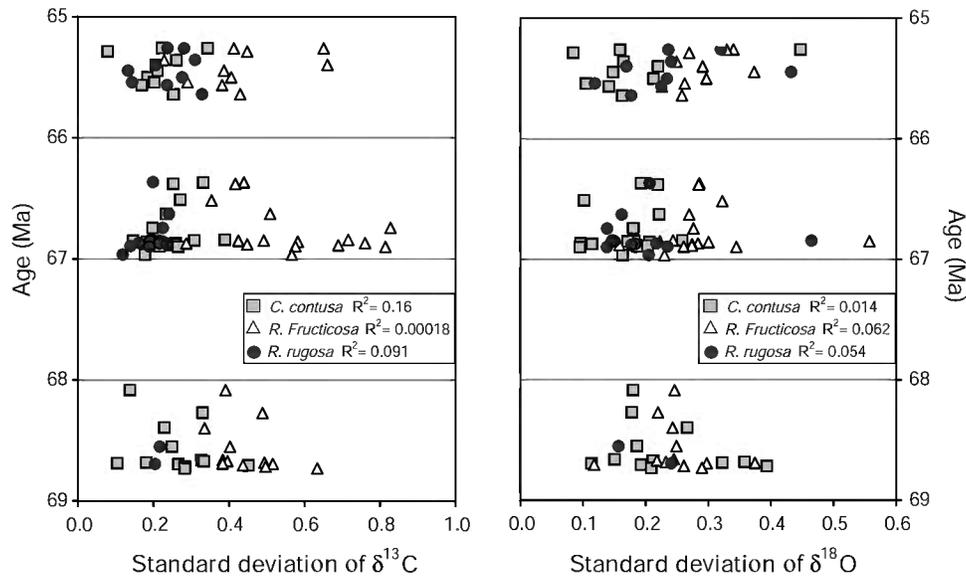
### 3.3. Long-Term Trends

[16] Across the stratigraphic interval studied, there is a long-term negative  $\delta^{18}\text{O}$  trend of  $\sim 1.5\text{‰}$  in all three taxa and a divergence in  $\delta^{13}\text{C}$  up section (Figures 4 and 5). There is no relationship between  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values among the three species at any scale (Figure 3). In addition, regression analysis demonstrates no significant correlation between

within-sample variability (quantified as  $1\sigma$  standard deviation) and depth for any of the three taxa. The  $R^2$  and  $P$  values of the standard deviation of  $\delta^{18}\text{O}$  values versus age are 0.062 and 0.14 (*R. fructicosa*), 0.014 and 0.48 (*C. contusa*), and 0.05 and 0.31 (*R. rugosa*); for  $\sigma$   $\delta^{13}\text{C}$  versus depth they are 0.00018 and 0.94 (*R. fructicosa*), 0.16 and 0.015 (*C. contusa*), and 0.091 and 0.18 (*R. rugosa*) (Figure 7).

## 4. Discussion

[17] This study revealed a remarkable degree of within-sample variability for the taxa studied that was also remark-



**Figure 7.** Standard deviation of within-sample isotopic values plotted against age [MacLeod *et al.*, 2005] with  $R^2$  values listed. There is no statistical relationship between depth and within-sample variability for any taxon in either isotope system.

ably consistent across the  $\sim 3$  Myr interval studied. Throughout the section the difference between individuals of the same species from the same sample was greater than 0.5‰ in both  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  and was up to 2.4‰ for the  $\delta^{13}\text{C}$  values of *R. fructifera*. With the exception of long-term trends toward larger size and both lower  $\delta^{18}\text{O}$  and lower  $\delta^{13}\text{C}$  values in *C. contusa*, there is no apparent correlation between size and isotopic results. Despite the high within-sample variability, consistent between-species differences are present, and secular patterns are apparent on both intermediate and long timescales.

#### 4.1. Within-Sample Variability

[18] Previous work [D’Hondt and Arthur, 1995; D’Hondt and Zachos, 1998; Houston and Huber, 1998; Houston *et al.*, 1999; Abramovich *et al.*, 2003] and our results (i.e., high within-sample intraspecific variability in  $\delta^{13}\text{C}$  and generally low  $\delta^{18}\text{O}$  values) strongly suggest that *R. fructifera* contained photosymbionts. Moreover, the lack of correlation between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values confirms that the high  $\delta^{13}\text{C}$  range ( $>1.5\%$ ) observed in *R. fructifera* is a signature of photosymbiosis and not the result of kinetic fractionation or ecotypic variation. Using *R. fructifera* as a model for expected photosymbiotic patterns, both *R. rugosa* and *C. contusa* are interpreted as asymbiotic.

[19] The  $\delta^{13}\text{C}$  results for *R. fructifera* explain a puzzling aspect of  $\delta^{13}\text{C}$  trends in photosymbiotic-bearing taxa. Consistent with earlier studies, Houston and Huber [1998] suggested that in a photosymbiotic organism a rapid rate of  $\delta^{13}\text{C}$  increase is observed in juvenile chambers and that this rate of change gradually decreases in adult chambers. They also found that this trend is sometimes reversed in the final chambers in the largest class size (i.e., there are lower  $\delta^{13}\text{C}$  values in the ultimate chamber than in the previous few chambers). Our results

demonstrate that large individuals from the same sample can have very different isotopic signatures (up to 2.4‰ difference). Inclusion of large individuals or chambers of large individuals with low  $\delta^{13}\text{C}$  values could easily bias results, especially since analyses of large individuals/large chambers typically use fewer specimens than analyses of small individuals.

[20] Lacking *R. fructifera*-style  $\delta^{13}\text{C}$  patterns, *R. rugosa* and *C. contusa* are both interpreted as asymbiotic, but they occupied different portions of the water column. The depth habitat of planktonic foraminifera can be inferred from simultaneous analysis of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  isotopic values [e.g., Boersma and Shackleton, 1981; Pearson *et al.*, 1997]. Carbon isotopes reflect mainly the equilibrium values between dissolved inorganic carbon and atmospheric  $\text{CO}_2$  modified by fractionation during photosynthesis in the photic zone and remineralization of organic matter at depth. This biological pump results in surface waters with higher  $\delta^{13}\text{C}$  ratios than deeper water. The oxygen isotopic ratio of test calcite reflects mainly the isotopic composition of seawater and the temperature of calcification. The general similarity of  $\delta^{18}\text{O}$  values of *R. fructifera*, *C. contusa*, and *R. rugosa* suggests that each species lived in the upper portion of the water column; any  $\delta^{18}\text{O}$  differences among the taxa were not well resolved at our sampling intensity. On the other hand,  $\delta^{13}\text{C}$  results clearly discriminate among the three taxa. The lowest average  $\delta^{13}\text{C}$  values are consistently observed in *C. contusa* (Figure 4 and 5), suggesting that *C. contusa* inhabited a relatively deeper niche in the water column compared to the other two species. If we accept that *R. fructifera* is photosymbiotic and that up to 1.5‰ of the  $\delta^{13}\text{C}$  value in the shell is the product of photosymbiosis [Spero and Williams, 1988; Spero and Lea, 1993; D’Hondt *et al.*, 1994], then the subtraction of this effect will yield  $\delta^{13}\text{C}$  values that are very similar for both *R. fructifera* and *R. rugosa*. This

correction suggests that both *R. rugosa* and *R. fruticosa* may have lived together in the surface mixed layer.

#### 4.2. Milankovitch-Scale Variability

[21] Milankovitch-scale cycles are well expressed in many variables in Hole 1050C (e.g., color,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ , magnetic susceptibility, and relative abundances of foraminiferal species [MacLeod *et al.*, 2001]), but the new results presented here show possible cyclicity only in averaged  $\delta^{18}\text{O}$  values for core section 16R-2 (Figure 6). Recalling the discussion of size-related trends in  $\delta^{13}\text{C}$  for photosymbiosis, we suggest this failure to observe strong cyclic variation in all taxa and intervals reflects a sampling bias. Specifically, the within-sample variability in  $\delta^{18}\text{O}$  is relatively low compared to expected  $\delta^{18}\text{O}$  cycle amplitude in core section 16R-2, whereas the opposite is true for  $\delta^{13}\text{C}$  and for  $\delta^{18}\text{O}$  in core section 13R-5. Thus averaging values for 10 individuals reveals cyclicity in  $\delta^{18}\text{O}$  for 16R-2, but this number of samples is not sufficient to average out variability between individuals in  $\delta^{13}\text{C}$  values or for  $\delta^{18}\text{O}$  values in 13R-5. Previous higher-resolution studies across color cycles in core sections 16R-2 and 13R-5 [MacLeod *et al.*, 2001; Isaza *et al.*, 2003] reinforce this conclusion. Both studies show that isotopic variability correlates with cycle amplitude, especially in fine fraction carbonate, but this cyclicity is more evident in foraminiferal data in section 16R-2 where 30–80 individuals were analyzed in a common acid bath [MacLeod *et al.*, 2001] than it is in section 13R-5 where only 2–10 individuals were analyzed in a Kiel device (single acid bath) [Isaza *et al.*, 2003].

[22] More important than this demonstration of potential sampling bias (and finding average  $\delta^{18}\text{O}$  values consistent with previous studies [MacLeod *et al.*, 2001; Isaza *et al.*, 2003]), the results from this study show no correspondence between within-sample variability and the Milankovitch cycles. That is, the lack of correlation between cycles and the within-sample standard deviations implies that differences observed at Milankovitch timescale are not strongly associated with changes in the magnitude of interannual variability.

#### 4.3. Long-Term Trends

[23] The largest isotopic shifts in the data set are apparent on long timescales. Three principal long-term trends are recognized. First, we observe an average negative  $\delta^{18}\text{O}$  trend of  $\sim 1.5\text{‰}$  in all three taxa (Figures 4 and 5), which would correspond to an increase in temperature of  $\sim 6^\circ\text{C}$  over the  $\sim 3$  Myr interval studied. Second, *C. contusa* shows parallel trends to lower  $\delta^{13}\text{C}$  values and larger test mass up section. An increase in size through the Maastrichtian has been previously documented for *C. contusa* [Kucera and Malmgren, 1998] and is consistent with the negative correlation between  $\delta^{18}\text{O}$  values and size in other planktonic foraminifera that has been interpreted as a response to increased surface water temperature [Schmidt *et al.*, 2003]. Finally, interspecies  $\delta^{13}\text{C}$  values diverge through time because of both the decrease in  $\delta^{13}\text{C}$  in *C. contusa* as well as a slight increase in the average  $\delta^{13}\text{C}$  values of *R. fruticosa* (Figures 4 and 5).

[24] The observed long-term trends are not easily explained by diagenesis, interannual/intra-annual variability,

or niche migrations. If diagenesis were responsible for the long-term observations, the within-sample standard deviation should be lowest in the most altered samples. Similarly, if long-term trends were correlated with interannual or intra-annual changes (e.g., seasonality), the within-sample variability should change systematically through the section. Such change is not observed for any taxon (Figures 4 and 7). Finally, congruent  $\delta^{18}\text{O}$  trends but divergent  $\delta^{13}\text{C}$  trends across taxa do not match the patterns expected if one taxon migrates to a new niche and otherwise the environment remains constant.

[25] Assuming that *C. contusa* was a deep surface dweller (at least compared to *R. fruticosa* and *R. rugosa*), the decrease in its  $\delta^{13}\text{C}$  values combined with the interspecies divergence could be an indicator of increasing water column stratification in the western Atlantic during the late Maastrichtian. Divergence in  $\delta^{13}\text{C}$  is also seen among three other planktic taxa, and increased stratification is also suggested by  $\delta^{18}\text{O}$  results and correlative diversification among planktic foraminifera [MacLeod *et al.*, 2000, 2005]. These changes could be the consequence of increased seasonality as the Cretaceous greenhouse waned. Pronounced seasonal differences could lead to a strongly developed seasonal thermocline or seasonal abundance peaks in different taxa. However, the lack of any change in within-sample standard deviation for any taxon in either isotope associated with the long-term trends argues against this hypothesis.

[26] Therefore changes in water column structure seem to be the best explanation for the long-term isotopic trends observed. Previous studies [Hay, 1995; Frank and Arthur, 1999; D'Hondt and Arthur, 2002] have suggested the North Atlantic became a site of downwelling during the Maastrichtian. If so, surface return flow from the South Atlantic into the North Atlantic could have imported Southern Hemisphere warmth, explaining both warming in the North Atlantic and correlative cooling in the South Atlantic [MacLeod *et al.*, 2005]. Another response to North Atlantic downwelling would be an intensification of the polar front resulting in a more strongly developed North Atlantic thermocline, i.e., increased stratification. An increase in surface water stratification, in turn, would explain the  $\delta^{13}\text{C}$  divergence among the planktonic foraminifera.

#### 5. Conclusions

[27] High within-sample variability in  $\delta^{13}\text{C}$  (up to 2.4‰) and low  $\delta^{18}\text{O}$  values observed for *R. fruticosa* are strong indicators of photosymbiosis in this taxon. Assuming that *R. fruticosa* was a photosymbiotic taxon, isotopic signatures for *C. contusa* and *R. rugosa* suggest they both were asymbiotic. Relatively low  $\delta^{13}\text{C}$  values indicate that *C. contusa* was a deep surface dweller compared to *R. fruticosa* and *R. rugosa*, which are both interpreted as shallow surface dwellers.

[28] Milankovitch cyclicity seems to be present in the taxa analyzed, but sampling biases make single-specimen analysis an inefficient way to investigate changes on this timescale. Regardless, lack of correlation in within-sample standard deviation shows that there is no apparent relationship between Milankovitch-scale cycles and patterns observed on either shorter (within sample) or longer timescales.

[29] Three important long-term trends were observed: (1) a negative  $\delta^{18}\text{O}$  trend of  $\sim 1.5\%$ , which would correspond to an increase in temperature of  $\sim 6^\circ\text{C}$  over the last 3 Myr of the late Maastrichtian, (2) increased size and decreased  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values in *C. contusa* through time, and (3) a  $\delta^{13}\text{C}$  divergence through time which could be the result of increasing water column stratification. As with Milankovitch-scale cyclicity, lack of trends in intraspecific within-sample variability through time argues against inter-annual or intra-annual variation (short timescale) or spatial ecological variability as the forcing mechanism for the long-term trends observed. Thus our observations suggest that the observed isotopic trends are the result of long-term changes in the water column. Specifically, we suggest

regional warming resulted from heat imported from the South Atlantic as surface return flow from the South Atlantic replaced waters sinking in the North Atlantic. Warmer surface waters and a more strongly developed thermocline due to an intensification of the North Atlantic polar front would result in increased stratification and explain  $\delta^{13}\text{C}$  trends without requiring a change in the ecology of the species analyzed.

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