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## RESPONSE OF CALCAREOUS NANNOPLANKTON TO CLIMATIC PERTURBATIONS AND THE LONG-TERM IMPACT ON COMMUNITIES

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by

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### ABSTRACT

Calcareous nannoplankton are single-celled, marine, haptophyte algae that secrete calcium carbonate plates. These organisms play an important role in the global carbon cycle and the marine food chain. The distribution of nannoplankton is controlled by environmental parameters such as temperature, nutrient availability, salinity, and irradiance. The future of nannoplankton is uncertain. Projected global warming over the coming century will result in oceanographic changes and acidification of the surface ocean. One way of better understanding the effects of climate on modern nannoplankton populations is to study their fossil record.

In this dissertation I present studies of three intervals from the geologic record: the Paleocene-Eocene Thermal Maximum (PETM), the Eocene epoch, and the middle Miocene transition (MMT). During these events, global warming or cooling occurred on varying time scales (tens of thousands to tens of millions of years). Nannofossil abundance counts are paired with geochemical records, modeling results, and multivariate statistical analyses to reconstruct the assemblage and environmental responses to climatic perturbations.

The global nannoplankton response to long-term warming and cooling was assessed for the Eocene epoch. We found that there is a large turnover in the nannoplankton assemblage at the height of the early Eocene climatic optimum (EECO) with the expansion of the genus *Reticulofenestra* and the replacement of *Toweius*. *Reticulofenestra* migrates from high latitudes to low latitudes with global cooling in the middle Eocene. The expansion of *Reticulofenestra* in the high latitudes coincides with a decline in thermal stratification and biological pumping efficiency, as indicated by vertical stable isotope gradients. We propose that warming in the early Eocene caused bottom waters to warm, which in turn led to a decrease in the vertical thermal gradient of the ocean and an increase in vertical mixing.

During the PETM, the global nannoplankton response varies regionally. Nannofossil counts from several different PETM studies were combined into one large database for multivariate statistical analyses. In addition, we used GENIE modeling results from the PETM to estimate changes in the export production along with temperature proxies across the event. Nannoplankton ecology is reevaluated using more quantitative methods than have previously

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been applied. We find that the nannoplankton community structure changed across the PETM and these changes persisted even after the event.

Cooling during the MMT in the eastern equatorial Pacific (EEP) impacted nannoplankton communities. Nannoplankton assemblage counts reveal an increase in equatorial productivity during the MMT and the Mi-3 glaciation. The change seen in the assemblage occurs concurrent with cooling as identified by benthic isotopes. This shows that high latitude forcing strengthened EEP upwelling. It is likely that Antarctic glaciation caused an increase in the latitudinal thermal gradient, intensifying wind patterns.

There are similarities in the response of nannoplankton to climate change in these studies. First, the amount of time the assemblage shift occurred over is proportional to the duration of climate change. Second, each study showed that there were long-term effects on the assemblage as a result of environmental change. Finally, in each instance there is evidence for an individualistic response of nannoplankton. These findings can be applied to modern nannoplankton in an effort to understand how climate will impact the community.

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### INTRODUCTION

Calcareous nannoplankton (including coccolithophores) are single-celled, phototrophic, haptophyte algae that secrete calcitic platelets. Nannoplankton are one of the most prolific phytoplankton groups in the world ocean and hold an essential position at the base of the food chain (Westbroek et al., 1993). In addition, these organisms play a vital role in the global carbon and carbonate cycles by supplying organic carbon and calcium carbonate to the deep ocean (Hay, 2004). The supply of nannofossil calcium carbonate to the deep oceans initiated carbonate compensation, which has provided a buffer against climatic influences since the Cretaceous Period (Ridgwell, 2005). The distribution of nannoplankton in the ocean is regulated by physical properties such as temperature, nutrients, and water stratification. Nannoplankton are typically found in higher abundances in low-nutrient, warm-water settings, while diatoms, their siliceous counterparts, have a peak abundance in cool-water, high-nutrient zones (e.g. Okada and Honjo, 1973).

Modern day global warming is expected to impact nannoplankton in several ways. One of the major effects of rapid input of carbon into the atmosphere is ocean acidification. Ocean pH has declined 0.1 units from preindustrial levels and is expected to decrease another 0.3-0.4 units by the end of the century under the IPCC "business as usual" scenario (Doney et al., 2009). Ocean acidification may have a negative effect on calcifying organisms. Culture studies of coccolithophores have yielded conflicting results as to the impact of pH on calcification (e.g. Riebesell et al., 2000; Iglesias-Rodriguez et al., 2008) while ocean samples suggest decreased calcification with increased CO<sub>2</sub> (Beaufort et al., 2011). Climate change is also expected to impact nannoplankton biogeography and ecology. Nannoplankton are projected to expand their distribution and become more abundant in areas typically dominated by diatoms (Cermeño et al., 2008), which in turn impacts primary production and the amount of organic carbon transported into the deep sea. However, prediction of future changes on the livelihood of nannoplankton is fraught with uncertainty.

An alternative means of understanding how climate change will affect nannoplankton in the future is to study past intervals of climate change. The fossil record of nannoplankton (nannofossils) is expansive and well documented. Nannofossils are abundant in pelagic sediments worldwide and extremely useful for biostratigraphy because of their relatively rapid evolutionary rates and dispersal. Because the distribution of nannoplankton is determined by physical variables, they are used in paleoceanographic studies as a way of tracking changes in temperature and nutrient levels.

To assess how nannoplankton responded to climate change in the geologic past, their impact on primary production, and the long-term effects of climate change on the fossil community, I chose three intervals, including both warming and cooling over differing durations, to compare how rates affect the assemblage (Figure *i*.1). The three intervals are the Paleocene-Eocene Thermal Maximum (5°C warming over 20 kyr), the middle Miocene transition (2°C cooling over 80 kyr), and the Eocene epoch (3°C warming over 4 myr and 7°C cooling over 17 myr). The rates of climate change in these intervals are slower than those projected for the future (global temperatures could rise as much as 5°C in the next century [IPCC, 2007]), but they provide insight into the effect of global change on assemblage and community shifts, ecological changes, and the dominant environmental variables.

### PALEOCENE-EOCENE THERMAL MAXIMUM

The Paleocene-Eocene Thermal Maximum (PETM) was a transient warming event at ~55.8 Ma that lasted for 120-170 kyr (Farley and Eltgrowth, 2003; Röhl et al., 2007; Westerhold et al., 2007; Charles et al., 2011). It is estimated that up to 6800 Pg carbon were released into the atmosphere (Panchuk et al., 2008) causing global temperatures to rise 5°C over 20 kyr (e.g. Kennett and Stott, 1991; Thomas and Shackleton, 1996; Röhl et al., 2000; Zachos et al., 2003). Nannoplankton assemblages have been extensively studied across this time interval from multiple sites across the globe. Nannoplankton display an increase in species origination and extinction rates during the PETM (Gibbs et al., 2006a) and taxa have been found that are restricted to the event (excursion taxa; Cramer et al., 1999; Monechi et al., 2000; Bralower, 2002; Kahn and Aubry, 2004; Raffi et al., 2005; Agnini et al., 2006, 2007a; Mutterlose, 2007; Raffi et al., 2009). Malformed taxa found during the PETM have been proposed to be a response to surface ocean acidification (e.g. Agnini et al., 2006; 2007a), but this hypothesis has been disputed (Bown and Pearson, 2009).

In general, results have shown a variable nannoplankton response at the PETM. Open ocean studies have concluded that assemblages reflect warmer and more oligotrophic surface water conditions (e.g. Bralower, 2002; Tremolada and Bralower, 2004; Gibbs et al., 2006b;

Tremolada et al., 2007) while shelf settings indicate enhanced productivity (e.g. Gibbs et al., 2006b). There are, however, numerous exceptions to these trends (Jiang and Wise, 2006; Agnini et al., 2007b; Mutterlose et al., 2007; Bown and Pearson, 2009; Raffi et al., 2009), and the response is not yet completely understood.

As a way of better understanding the global response of nannoplankton communities and the long-term impacts of transient global warming, in Chapter 2, we use multivariate statistical techniques on a global data set of nannofossil assemblage counts. We use these results to quantitatively reconstruct nannoplankton paleoecologies, separate the affect of temperature from nutrients, and show how the global community changed across the PETM.

### EARLY EOCENE WARMTH AND LONG-TERM COOLING

The Eocene epoch experienced both warming and cooling on million year time scales. The highest temperatures of the last 90 myr occurred during the early Eocene Climatic Optimum (EECO; 53-51 Ma) (e.g., Zachos et al., 2001). Sea surface temperatures (SSTs) from  $\delta^{18}$ O values show minimal change from the Paleocene-Eocene boundary through the EECO (Barrera and Huber, 1991; Dutton et al., 2005), but benthic temperatures increase ~3°C from 55-51 Ma (Zachos et al., 2001). The termination of the EECO initiated a 15 my benthic and surface cooling trend up to the Eocene-Oligocene (E/O) Boundary and the early Oligocene "Oi-1" glaciations as indicated by oxygen isotopes (e.g. Dutton et al., 2005; Zachos et al., 2001). Benthic temperatures decreased by ~7°C over 17 my (Zachos et al., 2001).

The conditions during the early Eocene greenhouse supported a diverse nannoplankton population (Bown et al., 2004). Species richness declined from the EECO to the E/O Boundary (Bown et al., 2004). Nannofossil studies from the Eocene have focused on shorter-term events, such as the PETM or the Middle Eocene Climatic Optimum (MECO; Bohaty and Zachos, 2003). However, none have focused on the long-term changes in nannoplankton assemblages and what drives them. In Chapter 1, we investigate how global nannofossil assemblages changed over the Eocene during a time of minimal or low extinction and origination rates (Bown et al., 2004) and what physical mechanisms were involved.

### MIDDLE MIOCENE TRANSITION

The middle Miocene transition (MMT; 13.9 Ma) marks the major expansion of the East Antarctic ice sheet (EAIS) at the Mi-3 glaciation (Shackleton and Kennett, 1975; Wright et al., 1992; Flower and Kennett, 1993) and is considered to be the final step in Cenozoic cooling to a modern-day-like ocean-atmospheric system (Vincent and Berger, 1985). This glaciation was rapid (it took ~80 kyr for ice to build up) and occurred at the end of a ~800 kyr cooling trend after the Miocene climate optimum (~17-14.7 Ma). Southern ocean records show that sea surface temperatures declined 7°C from the end of the climate optimum to Mi-3, ~2°C of which occurred over the MMT (Shevenell et al., 2004).  $\delta^{13}$ C tracers indicate that Southern Component Water (SCW) intensified after the MCO, and became strong at the MMT (Wright et al., 1992; Flower and Kennett, 1995). This time interval is similar to the middle-late Eocene cooling into the Oi-1 glaciation, but over a significantly shorter duration.

The MMT is within the Monterey carbon isotope excursion interval, an event hypothesized to be the result of enhanced oceanic productivity, as evidenced by the organic and phosphate-rich deposits found along coastal margins such as the Monterey Formation of California (e.g. Vincent and Berger, 1985; Mallinson and Compton, 1997). An alternative mechanism for this event is increased continental carbon burial (Föllmi et al., 2005; Diester-Haass et al., 2009).

The high latitude changes at the MMT could have had an impact on other parts of the globe, particularly equatorial upwelling zones. The formation of intermediate water in the Southern Ocean has been shown to supply nutrients to the thermocline at low latitudes (Sarmiento et al., 2004) and intensification in the formation of these waters could have led to an increase in the supply of nutrients. The increase in meridional temperature gradients associated with high-latitude cooling would have strengthened wind patterns and intensified upwelling (e.g. Vincent and Berger, 1985).

The nannoplankton record from the Miocene is robust, particularly the biostratigraphy. However, very few assemblage studies for this interval exist. In Chapter 3, I present the results of a study of nannoplankton assemblages from the Eastern Equatorial Pacific (EEP) that focuses on whether primary productivity increased at the MMT. In addition, this study seeks to elucidate how nannoplankton assemblages responded to climatic cooling both on short-term and longerterm evolutionary timescales. The findings of this dissertation show commonalities between each of the studies. The time span of nannoplankton assemblage change is proportional to the duration of climate change. For example, Eocene climate change takes place over millions of years, as does the shift in the nannoplankton assemblage. In each case, climate change results in a long-term change in the nannoplankton community, despite a return to prior environmental conditions. Finally, we see that nannoplankton taxa respond to climate change in an individualistic manner. A large component of the long-term changes observed in nannoplankton assemblages are taxa that adapted to new environments during the climate change interval and retained these new ecologic affinities. These results allow us to make projections on the influence of future global warming on nannoplankton populations.

**Figure** *i***.1.** The duration of climate change (log years) versusthe log rate of temperature change per thousand years for the Paleocene-Eocene Thermal Maximum (PETM), the middle Miocene transition (MMT), early Eocene warming (EEW), and middle-late Eocene cooling (MLEC). Modern day global warming is projected to increase 5°C over the next 100 years.



# CHAPTER 1: RESPONSE OF NANNOPLANKTON TO EARLY EOCENE OCEAN DESTRATIFICATION

### Leah J. Schneider, Timothy J. Bralower, Lee R. Kump

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### ABSTRACT

Nannoplankton play a significant role in the global carbon cycle; changes in the composition of the assemblage can influence primary productivity, carbon burial, and ultimately climate. Here counts of nannofossils in Eocene samples document one of the largest nannoplankton assemblage turnovers of the Cenozoic Era. This event is marked by the global expansion of *Reticulofenestra* at the termination of the early Eocene climatic optimum (EECO), and continues through the progressive cooling to the earliest Oligocene glaciation. To understand the mechanisms driving this assemblage shift we use multivariate statistical techniques and carbon and oxygen isotope records from localities worldwide. We find that the turnover in the global nannofossil assemblage is tied to thermal destratification of the ocean and a coincident decrease in the efficiency of the oceanic biologic pump at the height of the EECO. We propose that increased vertical mixing and increased nutrient supply to surface waters during the EECO caused a shift in the trophic structure towards enhanced productivity, influencing the global nannoplankton population.

### **INTRODUCTION**

Calcareous nannoplankton (including coccolithophores) are among the most prolific phytoplankton groups in the world ocean (Westbroek et al., 1993). These organisms have played a vital role in the global carbon cycle since the Mesozoic Era by supplying organic carbon and calcium carbonate to the deep ocean (Hay, 2004). The distribution of nannoplankton in the ocean is regulated by properties such as temperature, nutrients, and water stratification. In the modern ocean, nannoplankton are primarily found in higher abundances in low nutrient, warm water settings, while diatoms, their siliceous counterparts, have a peak abundance in cool water, high nutrient zones (e.g. Okada and Honjo, 1973). Predictions for modern global warming include a reduction in diatom productivity and wider ranges of nannoplankton species with increasingly warm, oligotrophic conditions (Cermeño et al., 2008), making studies of nannoplankton in ancient greenhouse intervals highly relevant for the future.

The highest temperatures of the last 90 m.y. occurred during the early Eocene Climatic Optimum (EECO; 53-51 Ma) (e.g., Zachos et al., 2001). Sea surface temperatures (SSTs), calculated from planktonic foraminifera  $\delta^{18}$ O values, changed little from the Paleocene-Eocene boundary through the EECO (Barrera and Huber, 1991; Dutton et al., 2005). SST proxies, such

as TEX<sub>86</sub> and U<sup>k</sup>, which are based upon glycerol dialkyl glycerol tetraether (GDGT) lipids and alkenones respectively, demonstrated greatly reduced latitudinal thermal gradients (Bijl et al., 2009). The termination of the EECO initiated a long benthic and surface cooling trend into the early Oligocene "Oi-1" glaciations as indicated by oxygen isotopes (e.g. Dutton et al., 2005; Zachos et al., 2001). In contrast to these trends, TEX<sub>86</sub> and  $\delta^{18}$ O extracted from "glassy" foraminifera indicate a warm, stable environment in an outer shelf region for the entire epoch (Pearson et al., 2007).

The conditions during the early Eocene greenhouse supported a widespread and diverse nannoplankton population (Bown et al., 2004). Changes in ocean circulation, water column structure, or climate during this time would affect nannoplankton populations, and, therefore, primary productivity and the carbon cycle. To this end, understanding the physical mechanisms and responses of nannofossil assemblages to changes in oceanography are of particular interest.

Calcareous nannofossils are useful paleoenvironmental indicators primarily based upon the ecologic associations of individual taxa. Haq and Lohmann (1976) and Haq et al. (1977) first mapped out Paleogene nannofossil distributions and used them to propose species groups as ecological indicators. Since that time, several studies have expanded on this work to determine the ecological significance of nannofossil taxa. However, the majority of these studies are qualitative and based upon inferences of environment, for instance temperature and nutrients are often assumed to co-vary. In Hallock's (1987) trophic resource continuum (TRC) concept, cool temperatures and greater nutrient availability coincide, whereas warm temperatures and limited nutrients correspond. Because nannofossil paleoecology has the potential to help shed light on paleoecology of individual taxa in terms of their temperature and nutrient tolerances, as well as their correlation with chemical environmental proxies, such as stable isotopes.

In this investigation we explore how global nannofossil assemblages change over the Eocene during a time of minimal or low extinction and origination rates (Bown et al., 2004). Our results indicate a dramatic nannofossil assemblage turnover event at the height of the EECO that was first noted by Haq et al. (1977), involving the expansion of the genus *Reticulofenestra*, the ancestor of the modern genera *Geophyrocapsa* and *Emiliania*. This event is correlated to the significant changes in the stable isotope values that indicate a decrease in water column stratification and in the efficiency of the oceanic biological pump. These changes could

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ultimately release  $CO_2$  into the atmosphere, elevating greenhouse conditions. The global shifts in nannofossil assemblages allow us to make new inferences on Eocene nannofossil paleoecology.

#### **METHODS**

The 192 samples for nannofossil study (Appendix Table A.1) were collected from cores at eight DSDP and ODP sites from a range of paleolatitudes (Figure 1.1a) through the Eocene (55-33.9 Ma). The average sampling resolution is lower than many micropaleontological studies (660 kyr), but because we are looking at the long-term assemblage evolution on a global scale, it is not feasible to have a high sampling resolution. However, to test whether a higher resolution sample set would alter the trends observed, we sampled the interval representing the onset of the EECO at all sites at an average 269 kyr resolution. The sites were selected based upon the reported preservation of nannofossils and the completeness of the Eocene section. Paleolatitudes were estimated from tectonic reconstruction maps of the Eocene (Ocean Drilling Stratigraphic Network; www.odsn.de). The localities are divided into three latitudinal categories: tropicalsubtropical, temperate, and polar. The tropical to subtropical localities are Site 1210, on Shatsky Rise in the North Pacific Ocean (32°13'N, 158°16'E; paleolatitude 18°-22°N) and Site 1263 on Walvis Ridge in the South Atlantic Ocean (28°32'S, 2°47'E; paleolatitude 30°S). The temperate sites are Site 762 on Exmouth Plateau, Indian Ocean (19°53'S, 112°15'E; paleolatitude 40°-45°S) and Site 549 on the Goban Spur in the North Atlantic Ocean (49°51'N, 13°05'W; paleolatitude 45°N). Two sites represent each of the polar localities. Sites 689 and 690 are from Maud Rise in the Atlantic sector of the Southern Ocean (64°31'S, 3°06'E; 65°10'S, 1°12'E; paleolatitude 65°S). Sites 1135 and 1137 are on Kerguelen Plateau, Indian sector of the Southern Ocean (59°42'S, 84°16'E; 56°50'S, 68°06'E; paleolatitude 60°S). All of the samples are composed of nannofossil ooze or chalk.

Samples (1-2 mg) were sonicated in buffered distilled water and allowed to settle out to remove large aggregates. An aliquot was extracted using a pipette and placed upon a smear slide, which was affixed to a microscope slide with Norland optical adhesive. Nannofossil counts of 300 specimens were performed at 1250x magnification. The counts include fragmented fossils with over half of the specimen preserved and specimens that could only be identified to the genus level due to preservational limitations (count data stored at the National Geophysical Data

Center, www.ngdc.noaa.gov). To test for reproducibility and significance, we counted a slide twice for 300 specimens, once for 500 specimens, and one count of 300 was performed for the same sample but prepared using a standard smear slide method (Appendix Figure A.1); the variations were not significant. The fossil preservation ranges from moderate to poor at each of the localities.

Carbon and oxygen isotopes from surface dwelling and benthic foraminifers were taken from the global compilation of Hilting et al. (2008) (see Hilting et al., 2008 and references therein). The isotope records from Maud Rise (Sites 689 and 690) (Kennett and Stott, 1990; Stott et al., 1990), Kerguelen Plateau (Site 738) (Barrera and Huber, 1991), and Shatsky Rise (Site 1209) (Dutton et al., 2005) use *Cibicidoides* spp. and/or *Nuttalides* spp. for benthic analysis and *Acarinina* spp. as the planktonic surface dweller, with the exception at Shatsky Rise where a combination of *Acarinina* and *Morozovella* species were used. We chose not to use thermocline values in this study because there exists uncertainty in the depth habitat of *Subbotina* spp. (Bralower et al., 1995; Dutton et al., 2005; MacLeod et al., 1990; Wade, 2004). However, thermocline oxygen and carbon isotopes are shown in Appendix Figure A.2.

Surface oxygen isotope values are used here as a proxy for sea surface temperature, recognizing the likelihood of diagenetic overprints and uncorrected salinity effects, using the equation of Epstein (1953):  $t(^{\circ}C)=16.5-4.3\delta+0.14\delta^2$ . The oxygen isotope gradient is used to investigate changes in thermal stratification, while the carbon isotope gradient is used to estimate the efficiency of the biological pump (see below). At Shatsky Rise and Kerguelen Plateau the gradients were calculated for samples in which both benthic and surface isotopes were measured. For Maud Rise, this was not possible because benthic and surface isotopes were not measured for the same samples and isotope data were placed in 0.5 Myr bins to calculate the gradient.

Ages of the samples for both nannofossil counts and stable isotopes were determined using a combination of reliable magnetostratigraphic and calcareous microfossil datums (Ali et al., 2000; Arney and Wise, 2003; Bralower, 2005; Bowles, 2006; Florindo and Roberts, 2005; Galbrun, 1992; Mueller, 1985; Pospichal and Wise, 1990; Shipboard Scientific Party, 2000; Shipboard Scientific Party, 2004; Siesser and Bralower, 1992; Snyder and Waters, 1985; Townsend, 1985; Wei and Thierstein, 1991; and Zachos et al., 2004) (Appendix Table A.2). The ages for the nannofossil datums are based upon the biostratigraphy methods used for IODP Expeditions 320 and 321 (Expedition 320/321 Scientists, 2010), which uses ages from

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Agnini et al. (2006), Agnini et al. (2007), Backman (1986), Backman (1987), Berggren et al. (1995), Blaj et al. (2009), Palike et al. (2006), and Villa et al. (2008). The Gradstein et al. (2005) time scale is used for the other datums along with the Cande and Kent (1995) age of the Paleocene-Eocene boundary (55.0 Ma). Age estimates for the P/E boundary range from 55.0-55.9 Ma (e.g. Westerhold et al., 2007). This potential error only affects samples at Maud Rise and Shatsky Rise between the P/E boundary and the next datum at 54.5 Ma. The depth of the P/E boundary was based upon the position of the carbon isotope excursion (CIE).

Nannofossil data were subjected to statistical analysis using the program R. The species counts were combined to produce a matrix of genera. Genera composing less than 2 percent of the assemblage were omitted to reduce variation in the analysis. A square root transformation, used to standardize the matrix, was chosen to minimize the influence of dominant taxa on the ordination. Non-metric multidimensional scaling (NMS), using the Bray-Curtis distance metric, was chosen as the ordination technique because it makes few underlying assumptions about the distribution of the data and seeks to preserve relative distances between the samples (McCune and Grace, 2002). This ordination has become popular in ecology (Clarke, 1993). NMS plots the distance between samples on a grid of a chosen number of dimensions by calculating scores until a minimum stress is reached. This technique seeks to display similarities, or dissimilarities, among samples. Samples with similar assemblage compositions will plot closely to one another and species will plot next to the samples that they are most common in. NMS provides a quantitative way of displaying many data in a single graph. NMS analyses were run for the global data set and for individual sites to observe how assemblages changed over time at a given locality. For the global genera matrix, the number of dimensions (k) was set at 3; for individual site NMS, k=2. Clarke (1993) stated, as a general rule, that stress values less than 10 indicate a good ordination fit, 10-20 a satisfactory fit, and >20 uninterpretable. An environmental fit (R function "envfit") was used to test the correlations between chosen variables and the NMS. For this test, vectors of values for the latitude and age of samples were constructed. The samples were coded 1, 2, or 3 based on their latitudinal grouping (tropical, etc.). Changes along a latitudinal gradient represent a change in the latitudinal biogeography of the assemblage.

### RESULTS

Nannofossil abundances show a very similar assemblage structure among sites located in a similar latitudinal zone (Figure 1.2). For each latitudinal division, the abundances of each genera are remarkably similar with a few exceptions in the late Eocene: a high Zygrhablithus population at Walvis Ridge, not found at Shatsky Rise; an increase in Cyclicargolithus at Exmouth Plateau, not found at Goban Spur; and a dramatic increase in Coccolithus at Maud Rise, not found at Kerguelen Plateau. Moreover, the magnitude and timing of abundance changes in each division are similar for the early and middle Eocene. Overall, there are three notable trends in the global assemblages throughout the Eocene (Figures 1.2 and 1.3): 1) a global decrease in *Toweius* spp. in the early Eocene, 2) a concomitant significant global increase in Reticulofenestra spp. in the early Eocene, and 3) a moderate decrease in warm-water affiliated taxa (i.e. *Discoaster* and *Sphenolithus*) at temperate and polar localities through the Eocene. Peak *Discoaster* abundance in the late Eocene at Shatsky Rise is likely due to preservational bias (Adelseck et al., 1973: Rea and Lyle, 2005); these samples contain particularly dissolved and overgrown nannofossils (Figures 1.2 and 1.3). The first occurrence (FO) of Reticulofenestra *dictvoda*, which is also the FO of the genus, is strongly diachronous, occurring at polar localities ~52 Ma and significantly later at temperate and tropical sites (Figure 1.1b). As evidenced by the FO ages, *R. dictyoda* migrated from the Southern Ocean northwards, inhabiting the South Atlantic and Indian Oceans (~51 Ma) before the North Atlantic and Pacific Oceans (48-50.8 Ma).

The NMS ordinations have a good fit to the data and are interpretable: all NMS trials have a stress less than 10: global, 8.76; Shatsky Rise, 9.8; Maud Rise, 6.77; and Kerguelen Plateau, 5.81. For the global NMS ordination, NMS axes 1 and 2 (NMS 1 and NMS 2) display the majority of the variance in the data set; NMS axis 3 is negligible. When all sites are run in the same ordination, the samples tend to array by locality (Figure 1.4) and there is significant overlap of samples from sites within the same climate region. The samples from Sites 689, 690, 1135, and 1137 plot horizontally along NMS 1; the other sites are arranged in an arch aligned with NMS 1. The major genera plot close to the samples in which they are most abundant. *Coccolithus* plots close to the origin and has a similar abundance in all of the samples. The environmental fit (envfit) function produced significant correlations between the samples and age and latitudinal zonation, with the vectors slightly offset from the axes. The correlation

between age and the NMS is  $r^2 = 0.67$  (p<0.001), and the correlation between latitude and the NMS is  $r^2 = 0.81$  (p<0.001).

#### DISCUSSION

The expansion of *Reticulofenestra* in the Eocene is one of the most significant nannofossil assemblage changes of the entire Cenozoic, with this genus rapidly assuming a large proportion of the global nannoplankton population. Paleoceanographic and climatic events often lead to the initiation or demise of a population by changing hydrography and other physical or biological variables (Norris, 2000). For example, during Oceanic Anoxic Event (OAE) 1a (Erba, 1994; Premoli-Silva et al., 1999), OAE 2 (Bralower, 1988; Leckie et al., 2002), and the PETM (e.g. Bralower, 2002) nannofossil turnovers occurred, caused by changes in the water column structure, the ocean temperature, or a combination of the two. Here we discuss the potential cause for this early Eocene assemblage shift and the change into *Reticulofenestra*-dominated oceans.

### Nannofossil Paleoecology

Assemblages from the globally distributed sites provide an opportunity to refine our understanding of the ecology of the dominant Eocene nannofossil genera. Several abundant genera have been assigned ecologic affinities: warm water, oligotrophic indicators are *Discoaster, Sphenolithus, Ericsonia*, and *Coccolithus* (Aubry, 1992; Bralower, 2002; Bukry, 1973; Edwards, 1968; Haq and Lohmann, 1976; Kelly et al., 1996; Persico and Villa, 2004; Wei and Wise, 1990); cool water, mesotrophic indicators are *Chiasmolithus, Toweius*, and *Prinsius* (Aubry, 1992; Firth and Wise, 1992; Haq and Lohmann, 1976; Wei and Wise, 1990).

The latitudinal distribution of abundances of the dominant genera observed here is consistent with these previous assessments of nannofossil ecology. *Discoaster, Sphenolithus Ericsonia, Neocrepidolithus, Girsia*, and *Pseudotriquetrorhabdulus* are abundant at the tropical-subtropical sites (Figures 1.2 and 1.4). The genera *Cyclicargolithus, Zygrhablithus, Campylosphaera, Coronocyclus,* and *Clausiococcus* are most abundant in temperate to tropical localities. The high latitudes had the highest abundances of *Toweius, Chiasmolithus, Isthmolithus,* and *Neochiastozygus. Coccolithus,* which has previously been labeled a warm water indicator for the early Eocene (Haq and Lohmann, 1976), is ubiquitous, but has a higher

abundance in the warm, early Eocene. *Reticulofenestra* has a temperate-polar range in the early Eocene, but becomes increasingly ubiquitous over the course of the epoch. The ecology of *Zygrhablithus* is not well understood but has been cited by different authors as favoring oligotrophic and mesotrophic conditions (Aubry, 1998; Bralower, 2002, Bralower and Kalb, 2010; Tremolada and Bralower, 2004; Villa et al., 2008). In the early Eocene this genus has a global distribution and peaks in temperate to tropical zones at ~50 Ma (Figures 1.2 and 1.3). *Zygrhablithus* primarily has a temperate to subtropical affiliation for the remainder of the epoch. These distributions are consistent with the aforementioned studies.

The goal of our NMS analysis is to place the ecological results in a more quantitative framework. NMS 1 is correlated with age where NMS 2 reflects nannofossil latitudinal provinciality; sites are separated based upon their environment. Samples and species that have negative NMS 1 values are more commonly found in the early Eocene versus those with positive NMS 1 values, which are more common in the late Eocene. Similarly, species with negative NMS 2 values are more abundant in high latitudes and those with positive NMS 2 values have higher abundances in low latitudes. *Toweius, Reticulofenestra*, and *Cyclicargolithus* have the highest or lowest NMS 1 values because these genera either go extinct or originate during the Eocene and are strongly tied to age, whereas the other taxa are found throughout the sections. Alternatively, genera such as *Toweius, Chiasmolithus, Zygrhablithus, Sphenolithus, Ericsonia*, and *Discoaster* have the highest absolute values along NMS 2, indicating that they are associated with particular environments. *Coccolithus* and *Reticulofenestra* plot in the middle of NMS 2 because they are ubiquitous and are found evenly at all localities.

The site trends of the NMS graph (Figure 1.3) indicate assemblage changes that are occurring over time. The Maud Rise and Kerguelen Plateau samples form a band along NMS 1, because the primary assemblage change is the shift from *Toweius* to *Reticulofenestra*. The trend for the other sites is more complex because Reticulofenestra does not replace Toweius at these localities. Instead, this trend records the transition from *Toweius* to *Discoaster* and *Zygrhablithus* and then the influx of *Reticulofenestra* creating an "arch." Based upon paleoecologies, this arching trend could be explained by increasing temperature; however, the abundance increases in *Discoaster* and *Zygrhablithus* occur at the end of or after the EECO and there is no indication of warming in the high latitude assemblage (Figure 1.3).

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*Reticulofenestra* species *R. dictyoda, R. reticulata, R. daviesii, R. umbilica, R. samodurovii,* and *R. wadeae* achieve their greatest abundance in temperate to high latitudes in this study, supporting previous interpretations for a mesotrophic ecology (e.g. Villa et al., 2008). The one species that does not follow this trend is *R. bisecta*. This species, which has also been classified under the genus *Dictyococcites* because of its enclosed central area, appears to have originated in low latitudes and spread into higher latitudes in the late Eocene (Figure 1.2); based upon its morphology and differing ecology, it should be classified under *Dictyococcites* rather than *Reticulofenestra*.

Nannofossil counts show that the greatest change in assemblages is with the first occurrence and expansion of *Reticulofenestra dictyoda*, the most ubiquitous member of the genus (Figures 1.2 and 1.3). Reticulofenestra dictyoda is believed to emanate from the Toweius *crassus* lineage, which showed a preference for high latitude environments (Gallagher, 1989; Haq and Lohmann, 1976). The origination of *Reticulofenestra* occurred in high latitudes at 52 Ma and rapidly replaced *Toweius* in the high latitudes at 51 Ma. Globally, *Toweius* becomes an insignificant portion of the assemblage at 51 Ma and dwindles to extinction in the middle Eocene (Figure 1.3; Perch-Nielsen, 1985). Toweius first declines at Shatsky Rise and is last abundant at Kerguelen Plateau, which is reflective of its cooler water affiliation. The first occurrence of R. dictyoda in temperate and tropical-subtropical regions occurs 1 to 4 million years after its FO in high latitudes (Figures 1.1b, 1.2). In temperate zones, Reticulofenestra replaced Toweius, and to some extent, Zygrhablithus, whereas in the tropical-subtropical regions it only replaced Zygrhablithus. At the same time in the tropical and temperate sections, there is an increase in Discoaster as well. Interestingly, a very similar trend is observed by Agnini et al. (2006) from the Tethyan Possagno section of Italy. Species of Reticulofenestra have been assigned a temperate to high latitude affinity, suggesting it was adapted to cooler conditions (see Villa et al., 2008 and references therein). Therefore, the abundance increase of R. dictyoda from high to low latitudes is a prime example of the ramifications of surface-water cooling. In fact, the global expansion of *Reticulofenestra* has been used as evidence for cooling and increased productivity during the Eocene (Aubry, 1992).

The interpretation for the nannofossil changes seen around the EECO is not straightforward. For the tropical and temperate sites, the assemblage changes could be attributed to warming. These four localities show an increase in *Discoaster, Zygrhablithus*, and to some

extent *Sphenolithus* and *Ericsonia* (Figure 1.3). The cool species *Chiasmolithus* and *Toweius* decrease across the interval. However, at Exmouth Plateau the peaks in the warm water species occur after the height of the EECO, and at Shatsky Rise and Goban Spur *Sphenolithus* decreases. The nannofossil assemblage in polar regions is better explained by cooling than warming. At Maud Rise and Kerguelen Plateau the warm water genera *Discoaster, Zygrhablithus*, and *Sphenolithus* decline while *Chiasmolithus* increases. The nannofossil assemblage shows changes at the EECO that are more complex than global warming and require further analysis using additional data, including stable isotopes.

### **Oceanographic Context of Reticulofenestra Origination**

The gradient in  $\delta^{13}$ C has been used as a proxy for oceanic biological pumping (OBP) strength (export productivity) in the past (e.g. Pierre et al., 2001), but in fact it is more correctly interpreted as a measure of OBP efficiency; a high gradient indicates an efficient pump, typical of low productivity zones, and a low gradient indicates an inefficient pump, characteristic of high productivity systems (Hilting et al., 2008; Sigman and Haug, 2003). In the modern ocean, inefficient biological pumping occurs in the Southern Ocean. In this setting phytoplankton are unable to utilize all of the nutrients and <sup>12</sup>C-rich CO<sub>2</sub> upwelling from the deep ocean, because of the limitations of light and micronutrient iron, resulting in the outgassing of CO<sub>2</sub> despite the high productivity rates (Sigman and Haug, 2003; Volk and Hoffert, 1985). Because the upwelling of CO<sub>2</sub> offsets the productivity flux, which is also rich in  ${}^{12}$ C, the  $\delta^{13}$ C gradient is low. Alternatively, the OBP efficiency is high in oceanic gyres because all of the nutrients are utilized. Through changes in the biological pump, nannoplankton production can influence atmospheric pCO<sub>2</sub> over millennial (e.g. Archer and Maier-Reimer, 1994; Sigman and Boyle, 2000) and even longer time scales (Hilting et al., 2008). Because the OBP has the potential to play an influential role in CO<sub>2</sub> regulation, it is necessary to understand how it works under both modern and greenhouse conditions.

The peak of the EECO has been linked to a decrease in the OBP efficiency (Hilting et al., 2008). A significant decrease in the surface-thermocline and surface-benthic  $\delta^{13}$ C gradient occurred at maximum benthic water temperatures, indicating that the OBP was less efficient at transporting nutrients from the surface to deep waters. Based upon modeling results, Hilting et

al. (2008) concluded that oceanic productivity and OBP efficiency regulated climate for much of the Eocene.

In their global compilation that spanned every ocean basin, Hilting et al. (2008) recognized a global decline in the  $\delta^{13}$ C gradient starting at ~53 Ma that reached a minimum at ~51 Ma followed by an abrupt reestablishment of the gradient. The fluctuations in the gradient can be attributed to changes in both the benthic and planktonic values. In addition to productivity and the OBP, benthic  $\delta^{13}$ C values are also controlled regionally by the source of the deep water; however, there is no evidence of a shift in deepwater formation at this time (Thomas, 2004). This decrease in the carbon isotope gradient, interpreted as a decrease in OBP efficiency, could have led to an increase in atmospheric CO<sub>2</sub>. Modeling results of Hilting et al. (2008) indicate a *p*CO<sub>2</sub> increase of ~400 ppm from the Paleocene-Eocene boundary to 51 Ma tied to the carbon cycle. This decrease in OBP efficiency coincides with the observed global changes in the nannofossil assemblage.

Stable isotopes, in conjunction with the nannofossil counts, give an indication of how genera respond to oceanographic changes. Three localities with available oxygen and carbon isotope data, Maud Rise Sites 689 and 690, Kerguelen Plateau Site 738, and Shatsky Rise Site 1209, all of which were included in Hilting et al.'s (2008) compilation, display the same trends in oxygen and carbon isotope values for the early Eocene that are seen globally: a decline in the carbon and oxygen isotope gradients during the EECO (Figure 1.5). This allows for a direct correlation of the nannofossil assemblage to the global  $\delta^{13}$ C record of Hilting et al. (2008). At Maud Rise, the decrease in the surface to benthic oxygen isotope gradient is primarily due to increasing surface  $\delta^{18}$ O, resulting in basically no thermal stratification for the remainder of the Eocene (Figure 1.5a). At the same time,  $\delta^{13}$ C of the surface and benthic waters converge as well, decreasing the gradient. At Kerguelen Plateau, surface  $\delta^{18}$ O increases during the early Eocene while the benthic values decrease; this too results in almost no thermal stratification from ~51 Ma to the EOB, with the exception of a middle Eocene peak centered around 45 Ma (Figure 1.5b). The carbon isotope gradients at Kerguelen Plateau decline from an early Eocene value of 2 to a minimum value of ~1 at 50-49 Ma; the trend is not as pronounced as a Maud Rise. At Shatsky Rise, surface  $\delta^{18}$ O increases, diminishing the thermal gradient (Figure 1.5c), a destratification that is also reflected in the carbon isotope gradient, which decreases from the P/E

boundary to the height of the EECO and remains low until the EOB. The  $\delta^{18}$ O values of planktonic foraminifera from low latitudes are more susceptible to diagenesis. At Shatsky Rise we observe the poorest preservation in the late Eocene and little variation in the early to middle Eocene. Therefore, although the absolute  $\delta^{18}$ O values may be altered, the trend observed in the  $\delta^{18}$ O gradient should remain unaffected.

During the 51 Ma event, the three sites have a surface to benthic  $\delta^{18}$ O gradient of 0-0.7 ‰, which corresponds to a temperature difference of as little as ~0-3°C globally (~0.25‰/1°C; Epstein et al., 1953). For comparison, the modern Southern Ocean has a temperature gradient comparable to these values, while modern equatorial regions have about a 30°C difference (World Ocean Atlas, 2009). A thermal gradient of 0-3°C is extremely small, which would have made for a weakly stratified water column. At the same time the surface-benthic  $\delta^{13}$ C gradient decreased from 2-2.5 to ~1‰ at all sites from 55-51 Ma. To the extent that these sites reflect global trends, then, thermal stratification generally decreased from the P/E boundary to ~51 Ma, matched by a decline in the biological pumping efficiency which remains relatively low until the Oligocene.

At Maud Rise, the percent *Reticulofenestra* and the site NMS closely follow the three isotopic proxies (Figure 1.5a). The increase in abundance of *Reticulofenestra* occurs rapidly, while surface temperatures, OBP efficiency, and thermal stratification markedly decrease. Similarly, at Kerguelen Plateau, percent *Reticulofenestra* and site NMS change in concert with decreasing isotope gradients (Figure 1.5b). In contrast, *Reticulofenestra* did not arrive in the tropics until well after the stratification collapse, but the site NMS values indicate an assemblage shift during this interval. In this case, it is the increasing *Zygrhablithus* and *Discoaster* abundances that drive the shift in NMS 1 (Figure 1.5c). Globally, there is a change in the nannofossil assemblages correlated to changes in the isotopic proxies.

The close parallels between the nannofossils and shifts in isotope values and gradients suggest that nannofossil assemblages responded globally to a decrease in thermal stratification and OBP efficiency. The expansion of *Reticulofenestra* appears to be initiated by the stratification collapse in high latitudes. Conversely, this stratification collapse also marks the global decline of *Toweius*. Tropical-subtropical and temperate assemblages responded differently with an increase in *Zygrhablithus* and *Discoaster* (Figure 1.2, 1.5). At Shatsky Rise,  $\delta^{18}$ O values

indicate a warming pulse starting at ~52 Ma, around the same time as the increase in *Discoaster* abundance, and remaining warm until ~48 Ma (Figure 1.5). Similarly, the  $\delta^{13}$ C gradient at Site 1209 is at its minimum from 51 to ~48 Ma, roughly corresponding to the elevated *Zygrhablithus* abundances. At the lower latitude sites, the *Discoaster* abundances may be reflecting a warming of the surface waters, while *Zygrhablithus* is responding to a decline in the OBP efficiency.

If the increase in *Reticulofenestra* or other changes in global nannofossil populations were responding to decreasing temperatures at the termination of the EECO, it would be expected that any changes would be unidirectional, i.e. sites would respond similarly. In this case, global cooling would be expected to allow for migration of 'cool' taxa, such as *Toweius*, Chiasmolithus, or Reticulofenestra into lower latitudes and result in a reduction of 'warm' species. A prime example of this trend, but in the opposing direction, is at Maud Rise during the PETM (Bralower, 2002). The transient warming at the PETM is marked by an influx of Discoaster and Sphenolithus in the very high latitudes. In fact, the different sites have varying assemblage responses to the stratification collapse and the termination of the EECO (Figure 1.2). At high latitudes, the abundance of *Reticulofenestra* increases, but at temperate to tropicalsubtropical localities, Zygrhablithus and Discoaster increase in abundance. Because there are two differing trends in the assemblage responses, it seems unlikely that a global cooling pulse at the end of the EECO is entirely responsible for the documented changes (e.g. Aubry, 1992). Instead, we propose that it is primarily water-column destratification that leads to the early Eocene expansion of *Reticulofenestra* at high latitudes and *Discoaster* and *Zygrhablithus* at temperate to tropical-subtropical latitudes. Global cooling post-EECO then leads to a global expansion of Reticulofenestra to the EOB. In NMS space the sites converge for the middle to late Eocene samples as time progresses along NMS 1 (Figure 1.4). This results from *Reticulofenestra* composing almost half of the assemblage at each site. There remains latitudinal provinciality during the late Eocene (modest separation along NMS 2).

Our hypothesis that water-column destabilization and then cooling are the drivers of these assemblage changes is reflected in the distribution of sites with respect to their isotopic compositions and how this evolves with time (Figure 1.6). Here, we take  $\delta^{18}$ O of the planktonic foraminifera to represent surface water temperature and the surface-benthic  $\delta^{13}$ C gradient to represent increasing OBP efficiency (as the gradient increases) or increasing nutrient availability (as the gradient diminishes). When samples from Maud Rise, Kerguelen Plateau, and Shatsky

Rise are plotted using these isotopic data as axes, they occupy different areas of the graph (Figure 1.6a). Maud Rise initially has relatively warm surface waters and an efficient OBP in the early Eocene, after which cooling occurs and OBP efficiency decreases. The  $\delta^{13}$ C gradient at Kerguelen Plateau is similar to that of Maud Rise and temperature significantly decreases, as indicated by the time arrow on Figure 1.6, without a significant change in OBP efficiency. At Shatsky Rise, the OBP efficiency is slightly lower than the other two sites in the early Eocene, but the values are comparable to those of Maud Rise from 55-53 Ma. At this site the OBP efficiency stays relatively constant while temperature decreases.

Viewed in terms of *Reticulofenestra* abundances, there appears to be a temperature and OBP efficiency threshold for the invasion of this genus (Figure 1.6a). *Reticulofenestra dictyoda* rapidly expands into these localities when the  $\delta^{13}$ C gradient declines below 2.3 and surface  $\delta^{18}$ O are greater than -0.8. Additionally, other genera can be plotted in a similar space (Figure 1.6b). *Toweius* has its greatest abundances in samples that have  $\delta^{18}$ O surface values between -0.4 and - 1.4 and a relatively large  $\delta^{13}$ C gradient of 1.9 to 2.3, slightly contradictory to the cool, higher nutrient regions this genus had been thought to occupy. *Discoaster* and *Sphenolithus* inhabit waters with surface temperature conditions similar to, but slightly warmer than, *Toweius* ( $\delta^{18}$ O of -0.5 to -1.6) and also have a high  $\delta^{13}$ C gradient of 1.1 to 2.5. *Chiasmolithus* occurs in greatest abundance in cooler water conditions,  $\delta^{18}$ O values between 0.5 and -0.6.

The early Eocene temperate-polar ocean supported a cooler-water assemblage. *Toweius* occurred in large proportions in these areas up until the stratification collapse at the EECO. The increase in vertical mixing with destratification would have supplied more nutrients from deeper waters and the mixed layer could have deepened out of the photic zone, creating new stresses on nannoplankton assemblages. This change of environment seemingly did not favor *Toweius* and the unique conditions it was adapted to, facilitating the expansion of *Reticulofenestra* into this open niche space. Stable isotopes indicate that SSTs and the OBP efficiency never returned to early Eocene values after the EECO in high latitude environments, potentially driving *Toweius* into extinction. At the same time, an increase of *Zygrhablithus* and *Discoaster* in tropical-subtropical and temperate localities may reflect the same hydrographic changes. Relative to other nannofossil taxa, these genera are heavily calcified, which led Aubry (1992; 1998) to suggest that they were adapted to a habitat near the thermocline like the Cretaceous nannoconids (Erba,

1994). An increase in the depth of the mixed layer could have aided these taxa by positioning them closer to the thermocline. This interpretation goes against the well-studied distributions of *Discoaster* that show this genus was adapted to oligotrophy (see section 4.1), but it is plausible that *Discoaster* could have been responding to warming conditions at Shatsky Rise and have been more tolerant to higher nutrient environments than other oligotrophic taxa. Another possibility is that it changed affinities over time. When *Reticulofenestra* begins to appear in temperate and tropical environments, the abundances of *Discoaster* decline, with the exception of Shatsky Rise. Based upon the warm-water affinity of *Discoaster* and the cooler-water affinity of *Reticulofenestra*, this change can be attributed to cooling.

The distribution of *Zygrhablithus* is not as straightforward. Recent studies have inferred that this genus was mesotrophic (Bralower and Kalb, 2010; Tremolada and Bralower, 2004; Villa et al., 2008), which would explain its abundance increase at the destratification event and its persistence at temperate localities throughout the Eocene. The decline in both the thermal stratification and OBP efficiency terminated at 51 Ma in conjunction with cooling deep waters.

#### **CONCLUSIONS**

Nannofossil counts show that the expansion of *Reticulofenestra* is one of the largest assemblage changes of the Cenozoic, with this genus comprising approximately 50% of the global nannoplankton population by the late Eocene. The initial rise of *Reticulofenestra* in the Southern Ocean corresponds to a major decline in the abundance of *Toweius*, which dwindles to extinction in the middle Eocene. The oxygen and carbon isotope records for the Southern Ocean and tropical Pacific indicate progressive thermal destratification during the EECO. Warming of deep-waters coupled with stable or cooling surface waters weakened the thermal stratification of the ocean, allowing for increased vertical mixing of nutrients and carbon dioxide. This could have been the cause of the concomitant decline in the  $\delta^{13}$ C gradient, a proxy for oceanic biological pumping efficiency. The enhanced influx of nutrients and more vigorous vertical mixing spurred changes in the plankton assemblages, such as the *Toweius-Reticulofenestra* crossover in polar environments, which is tightly coupled to the isotope shifts. This decline in OBP efficiency is also expressed by an increase of *Zygrhablithus* and *Discoaster* in tropical and temperate localities. These two genera either benefited from changes in the mixed layer, a slight warming at the end of the EECO, or an increase in nutrients. Global cooling drove the migration

of *Reticulofenestra* into new settings in lower latitudes and likely facilitated the evolutionary lineage in this genus.

### ACKNOWLEDGMENTS

We thank Anna Hilting for sharing her oxygen and carbon isotope dataset. We also thank Giuliana Villa and two anonymous reviewers for detailed and constructive comments that improved the quality of this manuscript. This research used samples provided by the Ocean Drilling Program (ODP) and the Deep Sea Reseach Project (DSDP). Research was supported by the Schlanger Ocean Drilling Fellowship from the Consortium for Ocean Leadership awarded to Schneider and by NSF Grant EAR06-28394 to Bralower and Kump. **Figure 1.1.** Map displaying (a) DSDP and ODP sites studied and (b) the approximate age and error (in Ma) of the first occurrence of the genus *Reticulofenestra* at each of the localities. Eocene (~50 Ma) tectonic reconstruction is from the Ocean Drilling Stratigraphic Network (www.odsn.de).



**Figure 1.2.** Percent abundance of major nannofossil genera at each location for the Eocene. The sites are separated into their respective biogeographic provinces: tropical, temperate, and polar. Late Eocene samples at Shatsky Rise are poorly preserved and are denoted on the graph. The grey shading along the time scale represents the timing of the carbon isotope gradient decline and EECO (see Figure 1.5).


**Figure 1.3.** Percent abundances for nannofossil genera at each site. The grey bar denotes the timing of the EECO and the black bar indicates the position of the stratification collapse.



Figure 1.3a

Figure 1.3b



**Figure 1.4.** Nonmetric multidimensional scaling (NMS) axes 1 and 2 for all samples and the major genera. Each sample is represented by a circle and the genera are represented with crosses. 'Age' and 'latitude' vectors are the result of the envfit analysis, which allows for axes 1 and 2 to be interpreted as a change in age ( $r^2=0.67$ ) and a change in latitudinal province, such as tropical, temperate, or polar ( $r^2=0.81$ ), respectively.



**Figure 1.5.** The  $\delta^{18}$ O surface record (red), the  $\delta^{18}$ O surface to benthic gradient (green), the  $\delta^{13}$ C surface to benthic gradient (blue), the NMS 1 values for individual sites (black), and the percentage of *Reticulofenestra* for (a) Maud Rise, (b) Kerguelen Plateau, and (c) Shatsky Rise. The standardized number of *Discoaster* (purple) and *Zygrhablithus* (grey) specimens are included for Shatsky Rise. At Kerguelen Plateau, nannofossil counts are from Site 1135 and the isotopes are from Site 738. Similarly, at Shatsky Rise the nannofossil data are from Site 1210 and the isotope are from Site 1209. The latitudes given are paleolatitude estimates. The decrease in thermal stratification and OBP efficiency during the EECO is shown with light grey shading, reaching a gradient minimum at 51 Ma (black line).

a) Maud Rise, Site 690







C) Shatsky Rise, Sites 1209/1210



**Figure 1.6.** (a) Surface  $\delta^{18}$ O and surface-deep  $\delta^{13}$ C gradient of samples from Shatsky Rise (red), Maud Rise (dark blue), and Kerguelen Plateau (light blue); the  $\delta^{13}$ C gradient is used as a proxy for oceanic biological pump (OBP) efficiency and the surface  $\delta^{18}$ O value is a proxy for temperature. The size of the symbols corresponds to the number of *Reticulofenestra* specimens in each sample. The greatest number of *Reticulofenestra* are found when the  $\delta^{13}$ C gradient is less than 2.3 and the surface  $\delta^{18}$ O is greater than -0.8. This threshold is marked by the black lines at these values and the grey shading on the area of the graph where *Reticulofenestra* is only found in very low abundance. The arrows show the relative stratigraphic trend of the samples over time at each site. (b) Similar plot of samples with peak abundances of other genera (*Sphenolithus* and *Discoaster*=purple, *Chiasmolithus*=blue, *Toweius*=red, and *Reticulofenestra*=orange), indicating the preferred environmental conditions.



200+	101-200	▼ 101-20		
101-200	1-100	▼ 1-100		
<b>1-100</b>	• 0	<b>v</b> 0		
. 0				

# CHAPTER 2: CALCAREOUS NANNOPLANKTON ECOLOGY AND COMMUNITY CHANGE ACROSS THE PALEOCENE-EOCENE THERMAL MAXIMUM

# ABSTRACT

The response of calcareous nannoplankton to warming at the Paleocene-Eocene Thermal Maximum (PETM; ~55.8 Ma) has been documented at several localities worldwide. Based upon the inferred paleoecology of taxa, it has been interpreted that open ocean localities became warmer and oligotrophic and there was enhanced production along shelf margins at the onset of the PETM. However, these paleoecological assessments are qualitative in nature and rely upon the taxonomic distributions and the relationship between temperature and latitude. Furthermore, it is difficult to disentangle the effects of temperature and nutrient availability upon nannoplankton distributions. Here we use multivariate analyses of a global dataset of nannofossil abundances to provide a quantitative way of establishing nannoplankton paleoecologies, separate the influence of temperature versus nutrients, and to characterize long-term changes in nannofossil assemblages. Our results show that at individual localities the relative importance of either nutrient availability or temperature on the assemblage varies. In addition to the transient assemblage shift, there is also evidence of adaptation and a long-term change in the nannoplankton community across the PETM that persists after the event. Finally, we use modeling results to support our interpretation that open ocean nutrient availability decreased at the PETM.

# **INTRODUCTION**

With growing concern about impact of global warming and associated environmental changes on marine communities, ancient warm intervals offer valuable lessons about the potential effects of climate change on life in the oceans. One of most applicable of such ancient intervals is the Paleocene/Eocene Thermal Maximum (PETM). The PETM occurred at ~55.8 Ma and lasted for ~120-170 kyr (Farley and Eltgrowth, 2003; Röhl et al., 2007; Westerhold et al., 2007; Charles et al., 2011). Sea surface temperatures (SSTs) increased by ~5°C in the tropics and by ~9°C at high latitudes and coastal ocean locations (Kennett and Stott, 1991; Zachos et al., 2003; Zachos et al., 2005; Sluijs et al., 2007), while bottom water temperatures increased by 4-5°C (Thomas and Shackleton, 1996). The PETM is characterized by dramatic changes in carbon cycling, including a global -4 to -5 ‰  $\delta^{13}$ C excursion (e.g. Kennett and Stott, 1991; Koch et al., 1995; Pagani et al., 2005; Cui et al., 2005). Combined, this evidence suggests input of large

amounts of CO<sub>2</sub> into the ocean and atmosphere as the dominant cause of the warming with possible sources from methane clathrates (Dickens et al., 1995; Thomas et al., 2002), thermogenic methane (Svensen et al., 2004), a bolide impact (Kent et al., 2003), extensive peat and coal oxidation (Kurtz et al., 2003), or permafrost thaw. Whatever the cause, the PETM resulted in major biotic changes across marine and terrestrial communities (e.g. Gingerich et al., 1980; Kennett and Stott, 1991; Maas et al., 1995; Hooker, 1996; Kelly et al., 1996; Thomas and Shackleton, 1996; Clyde and Gingerich, 1998; Wing et al., 2005; Gibbs et al., 2006a; Gingerich, 2010).

The calcareous nannoplankton, a group of haptophye algae that precipitate calcite skeletons and leave an extensive fossil record, were wide-spread primary producers in the open ocean during the PETM. Extensive research on this fossil group in PETM sections has centered on highly detailed analyses of assemblages and their changes during the event. Nannoplankton species show sharp increases in origination and extinction in response to the PETM (Gibbs et al., 2006a). Moreover, certain species are restricted to the interval encompassed by the isotope excursion (excursion taxa; Cramer et al., 1999; Monechi et al., 2000; Bralower, 2002; Kahn and Aubry, 2004; Raffi et al., 2005; Agnini et al., 2006, 2007a; Mutterlose, 2007; Raffi et al., 2009) and malformed taxa (Kahn and Aubry, 2004; Agnini et al., 2007a; Raffi and De Bernardi, 2008; Raffi et al., 2009) have been found. These malformed specimens may be a response to surface ocean acidification at the PETM (e.g. Agnini et al., 2006; 2007a), but this hypothesis has been contested (Bown and Pearson, 2009).

The paleoecology of nannoplankton taxa has been used to determine changes in surface water productivity and temperature across the PETM and the response of species to the environmental change varies at different locations. The prevalent interpretation is that there was widespread oligotrophy in the open ocean (e.g. Bralower, 2002; Tremolada and Bralower, 2004; Gibbs et al., 2006b; Tremolada et al., 2007), warming at high latitudes (Bralower, 2002; Jiang and Wise, 2007) and enhanced production along continental shelves and slopes (e.g. Crouch et al., 2003; Gibbs et al., 2006b; Agnini et al., 2007a; John et al., 2008). There are, however, several exceptions to these trends (Jiang and Wise, 2006; Agnini et al., 2007b; Mutterlose et al., 2007; Bown and Pearson, 2009; Raffi et al., 2009), which suggest a more heterogeneous global response.

Traditionally, nannofossil paleoecology has been determined by biogeography and inferences about the temperature and nutrient structure of the surface waters (e.g. Haq et al., 1977; Aubry 1992). In these instances, temperature and nutrients are assessed relatively by latitude and distribution of upwelling areas. By using inferred paleoenvironments to assign ecological preferences and then in turn using the nannoplankton distributions to interpret oceanic environments creates circular reasoning. Without the use of other evidence or proxies, it is difficult to get around this circular reasoning by solely using the nannofossil record.

Typically, in the open ocean, temperature and nutrients are described as correlated, with environments ranging from warm/oligotrophic to cool/eutrophic (Hallock, 1987), and the coupling of these two variables extends to the paleoecologic affinities of different taxa. In the case of the PETM, as well as other geologic events, these taxa are used to reconstruct surface water environments; however, because of the coupled nature of temperature and nutrient availability, there is significant uncertainty about which physical variable controlled assemblage change.

In an effort to assess nannoplankton paleoecology in a quantitative manner to get around circular reasoning, decouple temperature and nutrient effects, and test if the oceanic response varied regionally across the PETM, we use multivariate statistical techniques on an assemblage data set of over 500 samples from seven localities that cover a range of different oceanic settings. These data derive from the studies of Bralower (2002), Kelly et al. (2005), Gibbs et al. (2006b), Agnini et al. (2007a), Mutterlose et al. (2007), Raffi et al. (2009), and S.J. Gibbs (unpublished data from Bass River). We compare the assemblage data with geochemical records and model reconstructions. We use the integration of results to shed light on the similarities among sites, the role of environmental variables, and the paleoecology of nannoplankton genera across the PETM.

# **METHODS**

## Data Set

Nannofossil assemblage data through the PETM are compiled from studies completed at seven localities spanning multiple environments (Figure 2.1). Maud Rise (Site 690) is a high latitude, open ocean site; Walvis Ridge (Site 1263), Demerara Rise (Site 1260), and Shatsky Rise (Site 1209) are tropical to sub-tropical open-ocean localities; Forada, Italy is a hemipelagic locality; and Wilson Lake and Bass River, New Jersey, USA are near to distal shelf sites, respectively. For each data set the species counts were grouped at the genus level. Genera composing less than 2% of the assemblage were omitted from the analysis because rare species tend to form outliers in the multivariate analyses. Percents were then recalculated so that the genera included in the analysis make up 100% of the assemblage. Samples from 335.19 - 335.26 mcd at Site 1263 were excluded from the analysis because of low carbonate content and poor preservation. Two additional samples from Shatsky Rise Site 1209 were counted at the genus level from the post excursion interval (213.6 and 214.6 mcd). All statistical analyses were run in R (www.r-project.org) using the "vegan" package.

### **Cluster analysis**

Cluster analysis was performed to determine the hierarchical grouping of genera. Before the cluster analysis, the count matrix was divided through by samples totals. The Sørensen (Bray-Curtis) distance metric was chosen to measure distances in multidimensional space (McCune and Grace, 2002). Ward's method was used as the linkage method because it tends to form compact groups. Ward's method produced similar clusters to that of group averaging, but Ward's method resulted in less chaining and more compact groups.

The data set was divided into 5 time intervals: latest Paleocene, peak excursion (~0-74 kyr after onset), recovery stage 1 (~74-107 kyr), recovery stage 2 (~107-170 kyr), and the post excursion (>170 kyr). The cluster analysis methods discussed above were used on each time division. Because there are not detailed age models at all of the sites, these time interval divisions were made using carbon isotope stratigraphy and assigning approximate ages based upon Westerhold et al. (2007; Site 1263). The late Paleocene is assigned to samples below the negative  $\delta^{13}$ C isotopic excursion in either the bulk or benthic foraminifera record. The excursion interval (0 to 74 kyr after the onset) extends from the initial negative  $\delta^{13}$ C excursion to where the  $\delta^{13}$ C values begin to increase and return to pre-excursion levels. The first stage of the recovery (74 to 107 kyr after the onset) extends to the level where  $\delta^{13}$ C values returned to 80% of the values found after the CIE. Recovery stage 2 (107-170 kyr after the onset) includes the remaining samples up until the end of the PETM as determined by orbital age models. The post excursion (> 170 kyr after the onset) samples are from immediately after the PETM. Samples from later in the early Eocene are not considered because assemblages would express the longer-

term warming trend that extends from the top of the PETM into the early Eocene climatic optimum. The Wilson Lake and Bass River cores are not represented in the recovery and early Eocene data sets because sediments from these intervals were not preserved (Gibson et al., 2000).

#### **Detrended correspondence analysis**

A detrended correspondence analysis (DCA; Hill and Gauch, 1980) was used to ordinate the nannofossil percentages. DCA is a multivariate ordination technique that seeks to find gradients in datasets. The DCA was performed using the 'decorana' function in R and is an eigenvector technique that simultaneously ordinates species and samples (McCune and Grace, 2002). Commonly used in ecology, this technique assumes modal distributions of species along a gradient (Peet et al., 1988). While some prefer to use nonmetric multidimensional scaling (NMS) for ordination of ecological data because NMS makes no assumptions about the relationships among species, we found NMS and DCA produced similar results. DCA was performed on the genus count matrix following conversion of counts to proportions by dividing through by samples totals and then performing a square root transformation. This combination of transformations reduces the influence of dominant genera and increases the impact of rare taxa. Percent variance explained for axes 1 and 2 was calculated using the after-the-fact method.

Samples from Bass River and Wilson Lake that contained greater than 2% of *Hornibrookina* were omitted from these ordinations. *Hornibrookina* comprised up to 20% of the assemblage in numerous samples and the differences between these samples and the rest of the data set would have dominated the resulting DCA.

# **Model simulation**

We applied the  $C_{org}$  model simulation of Cui et al. (2011) to interpret how nutrient availability and productivity responded in different regions at the PETM. Cui et al. used the GENIE model, which is a three-dimensional ocean-atmospheric circulation model coupled with marine biogeochemical cycling (BIOGEM; Edwards and Marsh, 2005; Ridgwell et al., 2007). BIOGEM takes into account the transport of nutrients from the surface ocean and remineralization (Ridgwell et al., 2007). Cui et al. (2011) used the model to force CO<sub>2</sub> release (with an isotopic composition similar to typical organic carbon) to match the  $\delta^{13}$ C record from Spitsbergen, offset to match the atmospheric value. We interpret the GENIE results of biological  $PO_4$  uptake as a measure of production strength, the planktonic-benthic  $PO_4$  gradient as an indication of biological pump efficiency (Hilting et al., 2008), and the planktonic-benthic temperature gradient as a measure of ocean stratification.

#### RESULTS

#### **Cluster Analysis**

The cluster analysis of taxa for the entire data set yields two primary groupings: one containing genera typically found in high abundances in open ocean environments and the other containing genera found along, but not exclusive to, shelf settings (Figure 2.2). These are then further subdivided into five clusters. The first sub-group consists of *Biscutum, Ericsonia, Chiasmolithus, Zygrhablithus, Prinsius,* and *Octolithus*. All of these genera, with the exception of *Octolithus*, are primarily found at Maud Rise. The second sub-group is composed of *Campylosphaera, Discoaster, Sphenolithus, Fasciculithus,* and *Thoracosphaera. Discoaster, Sphenolithus*, and *Fasciculithus* were distributed globally during the PETM, but have the highest abundances in lower-latitude sites. *Campylosphaera* is found in the New Jersey shelf sections, but it peaks in abundance at Shatsky Rise and Demerara Rise. *Thoracosphaera* is found at Shatsky Rise and Forada, Italy. The third sub-group contains only *Coccolithus* and *Toweius*, which are ubiquitous genera. Each is found in significant abundance at the majority of the localities.

The shelf cluster is divided into two groups: genera that declined during the PETM and those that increased during the event. *Calciosolenia, Zygodiscus, Zeugrhabdotus*, and *Hornibrookina* decline from the late Paleocene into the PETM (Gibbs et al., 2006b). The remaining genera, *Coronocyclus, Neochiastozygus, Cruciplacolithus, Ellipsolithus, Neococcolithes, Pontosphaera*, and *Rhomboaster*, increase in abundance during the PETM (Gibbs et al., 2006b).

The cluster analyses for the late Paleocene, peak excursion, and recovery stage 1 are similar to the cluster of the entire data set (Figure 2.3) and display the same groups. Recovery stage 2 and the post excursion have a mixture of open ocean and shelf taxa within the groupings and the *Chiasmolithus-Ericsonia-Zygrhablithus* association is not present as in the other intervals.

#### **Detrended correspondence analysis**

The DCA for the dataset yields distinctive groupings for each site (Figure 2.4a). Maud Rise plots on the right side of the graph. Over time, samples get closer to the other sites, indicating that they become more similar (Figure 2.4a). Forada plots near the origin and the Walvis Ridge, Shatsky Rise, and Demerara Rise sites become progressively negative along DCA 1. The oldest samples from Bass River and Wilson Lake have values similar to those at Forada. Through the PETM, sample values at these two sites decrease along DCA 1 and increase along DCA 2. The genera in this data set have a widespread distribution along DCA 1 while the majority of them plot close to zero on DCA 2 (Figure 2.4b). DCA axis 1 accounts for 76.3% of the variance in the matrix and axis 2 accounts for 14.7%.

#### DISCUSSION

## **Global Nannoplankton Ecological Analysis**

The multivariate analyses provide a quantitative, global basis for determining nannoplankton paleoecology and tracking community changes across the PETM. Previous studies of nannoplankton paleoecology have been qualitative in nature because they typically rely upon interpretation of biogeographic distributions and changes in abundance across environmental gradients (e.g. Haq and Lohmann, 1976; Aubry, 1992; Bralower, 2002; Gibbs et al., 2006b). The presented statistical analyses represents a robust data set of taxa abundances across a range of environmental gradients and allows for a quantitative interpretation of the ecological similarity of different taxa and in what type of environment they are likely to occur.

The global cluster analysis divides the nannofossil genera by oceanic settings and environmental preferences (Figure 2.2). The cool-water cluster is mostly composed of genera that are well established as having cool-water and meso- to eutrophic affinities (Table 2.1). Similarly, the warm water cluster contains taxa that are traditionally used as warm water/oligotrophic indicators. The third group within the open ocean cluster contains *Coccolithus* and *Toweius*, both of which are widely distributed and are thus considered to be ubiquitous.

The height of the clusters is a measure of the grouping of genera in samples and can be interpreted in terms of similarity of their ecologies. *Biscutum* and *Ericsonia* have a very strong association, along with *Chiasmolithus* and *Zygrhablithus*, implying very similar paleoecologies.

Further separated from these cool water-affinity taxa are *Octolithus* and *Prinsius*, which have a strong association with one another. The warm water oligotrophs, *Discoaster*, *Sphenolithus*, and *Fasciculithus* cluster tightly, while *Campylosphaera* and *Thoracosphaera* are farther removed.

The shelf-hemipelagic cluster is composed of genera that are found in the New Jersey sections, Wilson Lake and Bass River. The first hemipelagic group peaks in abundance just below the CIE and then declines. The peak of *Hornibrookina* is concomitant with the Apectodinium acme, which has been interpreted as signaling elevated surface temperatures (Sluijs and Brinkhuis, 2009). Other taxa in this group, such as *Calciosolenia* and *Zeugrhabdotus* have been interpreted as productivity indicators (e.g. Bown, 2005). The second group increases in abundance at the CIE in the New Jersey sections. Gibbs et al. (2006b) interpreted this change as an increase in shelf production. However, the abundance of Apectodinium declines at the CIE in both sections and the dinocyst assemblage is composed of low-salinity tolerant groups thereafter (Sluijs and Brinkhuis, 2009). The estimated salinity decrease of 3-4 ppt (Zachos et al., 2006) could mark the difference between a euryhaline and mesohaline environment and was evidently enough to alter the dinocyst assemblage; such a change in salinity has the potential to cause the changes seen in the nannoplankton community. Thus, in addition to enhanced production, this assemblage may also indicate high temperatures and low salinity. *Rhomboaster*, which is found throughout the global ocean, is found within this cluster as a result of its restriction to the peak excursion interval.

The late Paleocene cluster is very similar to the global cluster analysis and contains five groupings, which we interpret to represent cool water/mesotrophic, temperate/mesotrophic, warm/oligotrophic, ubiquitous, and shelf/hemipelagic communities (Figures 2.2, 2.3a). The same groups exist during the peak excursion (0-74 kyr after the onset) and stage 1 recovery (74-107 kyr) intervals with some modifications, most notably an increase in the number of genera in the warm water group and a decrease in the cool water group (Figure 2.3b, c). The stage 2 recovery (107-170 kyr) and early Eocene (>170 kyr) intervals are notably different from the previous intervals (Figure 2.3c,d). At the stage 2 recovery, the cool water/mesotrophic group no longer exists and this trend persists after the excursion. *Chiasmolithus, Zygrhablithus, Ericsonia*, and *Toweius* were still abundant in the high latitudes, but the loss of *Biscutum* and *Prinsius* and the extensive geographic ranges of *Zygrhablithus, Toweius*, and *Chiasmolithus* create a less distinctive province compared to that of the late Paleocene. The shelf/hemipelagic has fewer

species in the recovery and post excursion clusters because there are no New Jersey samples available for this interval.

Certain clusters of taxa persist throughout the study interval while others change associations rapidly. *Chiasmolithus* and *Zygrhablithus* group together across the PETM, despite their change from the cool water cluster to the warm water cluster. These genera shared a common ecology and responded to climate change in a similar manner. *Octolithus* and *Prinsius* have similar changes in abundance at Forada and cluster tightly across the PETM. Similarly, *Discoaster, Sphenolithus*, and *Fasciculithus* cluster together in all of the time intervals indicating a shared affinity for warm water, oligotrophic environments across the PETM. *Coccolithus* and *Toweius* are found globally and link together. *Ericsonia* clusters with different groups across the PETM, starting out in the cool water group and joining the mesotrophic/temperate group by the end of the excursion. This suggests that *Ericsonia* adapted to slightly warmer conditions during the PETM.

The cluster analysis confirms previous interpretations of early Paleogene nannoplankton paleoecology (see Table 2.1 and references therein), but it does so by using a robust, global data set of hundreds of samples, applying statistical methods to construct species associations. However, of more significance, the time series of cluster analyses reveals that there were major changes in the nannoplankton community structure, the types of taxa and their relative proportions, across the PETM and indicate the loss of a high-latitude assemblage during the recovery interval, issues that will be further discussed in the following sections.

### Changes in nutrient availability during the PETM

It is well established from multiple proxies that temperature increased globally during the PETM (e.g. Kennett and Stott, 1991; Tripati and Elderfield, 2004; Zachos et al., 2006; Sluijs et al., 2011). However, to what degree surface nutrient concentrations and primary production were affected is uncertain. Most interpretations of nutrient level changes are based on microfossil assemblages, which we have seen are influenced by temperature as well. Independent evidence, such as sedimentation rates and radiolarian and dinoflagellate records, from the New Jersey Shelf and Forada, Italy indicates that productivity increased at the PETM (Cramer, 1999; Giusberti et al., 2007; Sluijs et al., 2007; John et al., 2008), but interpretations of decreased nutrient levels at open-ocean sites hinge on interpretation of fossil assemblages that often disagree with

interpretations of geochemical data (Bains et al., 2000; Stoll and Bains, 2003; Stoll et al., 2007). As an alternative method of approximating nutrient levels during the PETM, we observe how surface conditions changed regionally in Cui et al.'s (2011) model. The model resolution is too coarse to capture the New Jersey shelf margin, but all other sites are included (Figure 2.5). In this model, the majority of environmental change takes place in the first 20 kyr after the onset of the PETM.

Late Paleocene temperatures as determined by the model compare favorably to the temperature proxies as do the PETM temperatures (Figure 2.6b, d). The model does overestimate temperatures during the PETM at low latitudes (Shatsky Rise and Demerara Rise).

During the late Paleocene model values indicate that Demerara Rise and Maud Rise have the highest biological PO<sub>4</sub> uptake, with values of 10.3 and 9.1  $10^{-7}$ mol kg<sup>-1</sup> y<sup>-1</sup>, respectively. Forada has the next largest PO<sub>4</sub> uptake with a value of 7.4  $10^{-7}$ mol kg<sup>-1</sup> y<sup>-1</sup>. The most oligotrophic sites are Walvis Ridge (4.6  $10^{-7}$ mol kg<sup>-1</sup> y<sup>-1</sup>) and Shatsky Rise (2.9  $10^{-7}$ mol kg<sup>-1</sup> y<sup>-1</sup>).

The model simulation shows a global decline in export production (measured as mol POC y<sup>-1</sup>) of 7% (4.94-4.55  $10^{14}$  mol y<sup>-1</sup>) during the PETM (Figure 2.7). In the model, open ocean sites display a decrease in biological PO<sub>4</sub> uptake ranging from 0.3 to 0.8  $10^{-7}$  mol kg<sup>-1</sup> y<sup>-1</sup>, or 3-10%, indicating a decrease in the primary productivity (Figure 2.5). The Demerara Rise and Maud Rise areas were considerably more productive than Shatsky Rise and Walvis Ridge. The largest decrease in production strength is at Maud Rise in the Southern Ocean (0.8  $10^{-7}$  mol kg<sup>-1</sup> y<sup>-1</sup>). However, proportionally Shatsky Rise, Walvis Ridge, and Maud Rise show a 9-10% decline in PO<sub>4</sub> uptake. The decrease in PO<sub>4</sub> uptake is much smaller at Demerara Rise, with only a 3% change.

The increase in productivity at Forada (Giusberti et al., 2007) is reproduced in the model simulation (Figure 2.5). PO<sub>4</sub> uptake increases by 8%, or by 0.6  $10^{-7}$ mol kg<sup>-1</sup> y<sup>-1</sup>. Interestingly, at all of the sites, the biological PO<sub>4</sub> uptake is greater after the main carbon pulse than before.

With the exception of Maud Rise, the model simulations corroborate productivity changes as indicated by nannoplankton and other proxies (Figure 2.6a, c). Barite accumulation rates and Sr/Ca of coccoliths indicate an increase in productivity at Maud Rise during the PETM (Bains et al., 2000; Stoll and Bains, 2003), though both of these proxies have been contested (Dickens et al., 2003; Bralower et al., 2004). However, the fossil assemblage (Bralower, 2002),

CaCO<sub>3</sub>% accumulation rates (Farley and Eltgroth, 2003), and the model simulation all suggest a decline in productivity at Maud Rise during the PETM.

Each of the regions displays an increase in vertical stratification (planktonic-benthic temperature gradient) between 0 and 20 kyr (Figure 2.5). The gradient declines by 0.1 to 1°C. The temperature gradient after 20 kyr is less than values at 0 kyr. The slightly diminished thermal stratification after 20 kyr could be responsible for the enhanced PO<sub>4</sub> uptake through increased vertical mixing during the recovery period.

The modeled planktonic-benthic PO<sub>4</sub> gradient became larger in all of the regions at the onset of the PETM, indicating that biological pumping efficiency increased (Figure 2.5). Pumping efficiency is greatest at Forada followed by Demerara Rise, Walvis Ridge, and Shatsky Rise, all of which have similar planktonic-benthic gradients. Maud Rise has the smallest gradient indicating the least efficient pumping. Efficient biological pumping is typically found in oligotrophic regions whereas inefficient pumping is found in well-ventilated areas of high productivity (Sigman and Haug, 2003). This further supports the argument for increased oligotrophy in open ocean sites during the PETM. The Forada region also displays increased biological pumping efficiency despite the increase in nutrients. Previously it has been concluded that nutrient concentrations declined in the open ocean based upon fossil assemblages (e.g. Bralower, 2002; Gibbs et al., 2006b), the ecology of which have been inferred from biogeography creating a circular argument. The model simulation provides an independent estimate of nutrient availability and supports the notion that open ocean productivity declined.

### **Temperature and nutrient effects**

Nutrient concentration and temperature changes during the PETM are inferred from proxies and model results at each site (Thomas et al., 2002; Zachos et al., 2003; Tripati and Elderfield, 2004; Zachos et al., 2005; Sluijs et al., 2007). The variance along the global DCA axes 1 and 2 can be explained by temperature and nutrient levels, allowing us to separate the effect of these variables on the environment of the study sites as well as on the different nannoplankton taxa (Figure 2.6). From the above temperature proxies, paleolatitudes, and model results, temperature accounts for most of the variance (76.3%) in the data set and forms a gradient along axis 1 (Figure 2.6b, d). Nutrient availability appears to correspond to axis 2 (14.7%), as indicated from comparisons to the model results and to New Jersey productivity

records (Figure 2.6c). The one outlier is Demerara Rise, which, based on the model results, had the highest productivity yet plots near the oligotrophic sites. However, the DCA 2 values for Demerara Rise do not differ greatly from Forada or Maud Rise.

The global DCA ordination shows that the cluster groupings (i.e. Figures 2.2, 2.3) plot in distinctive areas (Figure 2.4b). In general, the cool, mesotrophic taxa plot positively on DCA 1 and warmer water taxa and the shelf-hemipelagic group plot from close to zero to negative values along this axis (Figure 2.4b). For DCA 2, taxa with a higher nutrient affiliation plot positively and more oligotrophic taxa plot below zero. The arrows on Figures 2.4a and 2.6 denote stratigraphic (i.e. temporal) trends of the samples for each site. The spread of the samples from each site are a visual representation of how much the nannoplankton assemblage changed. Based on correspondence of axis 1 with temperature and axis 2 with nutrient levels, we reconstruct how surface habitats changed at the study sites during the PETM and compare our results with previous, qualitative interpretations. Moreover, DCA allows us to determine the relative effect of temperature and nutrient levels on assemblages, which was not possible with the qualitative studies. The samples from Maud Rise show a shift towards warming and oligotrophy during the PETM, similar to the interpretations of Bralower (2002) and Kelly et al. (2005), but suggest that temperature was a more important factor (Figure 2.4a, 2.6). The samples at Maud Rise show the most spread of all the open ocean localities, which signifies the large shift in the nannoplankton assemblage. The trends at Shatsky Rise and Walvis Ridge are similar and support interpretations of warm water/oligotrophy by Gibbs et al. (2006b) and Raffi et al. (2009). The DCA paths for the two sites plot towards increased oligotrophy with a minor amount of warming, indicating that nutrient availability was more influential on communities than temperature. Demerara Rise primarily shows a shift towards higher temperatures, but also a decline in nutrient availability. The relatively small spread in the samples from Demerara Rise along axis 2 is consistent with the productivity modeling results that show only a 3% decrease in biological PO<sub>4</sub> uptake (Figure 2.5). This contrasts with the interpretations of Mutterlose et al. (2007) and Jiang and Wise (2006) who determined there was either no change in productivity or an increase in primary production, respectively. The New Jersey sections have a very large shift towards higher temperatures and eutrophication, which compare favorably to the studies of Gibbs et al. (2006b) and Sluijs et al. (2007). There is likely a salinity component that is additionally contributing to the shift at New Jersey. Like Maud Rise, the large range in the New

Jersey samples denotes a significant change in the nannoplankton assemblage. Finally, the samples at Forada form a tight cluster, but the minor trend that is present shows a slight shift to warmer temperatures and increased nutrient levels as described by Agnini et al. (2007). In summary, our interpretations are generally comparable to those of previous studies, but DCA allows us to partition the amount of the assemblage change caused by temperature and nutrient levels. Moreover, the data clearly suggest that the changes in the nannoplankton community that occurred in the shelf and high latitude sections were larger than those in the warmer open ocean.

## Ecological and community changes across the PETM

The statistical analyses reveal the evolution of the nannoplankton community across the PETM and indicate there is a definitive change in community organization during and after the PETM that has not been observed in other studies. The cluster analyses show a progression of the mesotrophic, cool-water, high-latitude community from one that has a distinctive assemblage to one that is composed of cosmopolitan taxa. Even though the high-latitude genera are similar before and after the PETM, they become more pronounced in oligotrophic settings in the Eocene (e.g. *Zygrhablithus;* Schneider et al., 2011). This could be a result of the high-latitude taxa adapting to widespread oligotrophy during the PETM and retaining this ecology even after temperatures had returned to late Paleocene values.

Nannoplankton taxa are thought to have changed ecological preferences through time; examples of this include the transitions of *Coccolithus pelagicus* and *Sphenolithus* from warm, oligotrophs in the Paleogene to mesotrophs in the Neogene (e.g. Haq, 1980; Wei and Wise, 1990; Aubry, 1992; Wade and Bown, 2006). The cluster analyses also show genera switching ecological groups, such as *Ericsonia, Campylosphaera, Zygrhablithus*, and *Chiasmolithus* among others. This is further evidence that taxa were adjusting to changing conditions across the PETM.

One could argue that the nannoplankton community had simply not yet recovered from the PETM by the end of the CIE and samples from later in the early Eocene should be considered. This seems unlikely, as global temperatures recovered to pre-PETM values at the end of the CIE. Furthermore, the long term warming trend of the early Eocene would be expressed in the assemblage data. Our sample coverage of the PETM is sufficient to support our interpretations The modifications of the nannoplankton community during the PETM persisted after the event despite a return to pre-excursion temperatures. It appears that the ecologies established during the PETM endured into the Eocene. The transient event not only contributed to evolutionary turnover, such as the extinctions of *Fasciculithus* and *Prinsius* (e.g. Agnini et al., 2007a), but also had a long-term impact on nannoplankton community structure.

This view on the long-term impacts of the PETM is novel. Individual site studies have focused almost exclusively on the nannoplankton changes associated with the onset of the CIE, with the exception of the global decline in *Fasciculithus* populations and the extinctions of *Fasciculithus* and *Prinsius* (e.g. Bralower, 2002; Gibbs et al., 2006b; Agnini et al., 2007; Raffi et al., 2009). Even the muted extinction and origination rates across the CIE suggest that the PETM had few lingering effects on nannoplankton assemblages (Gibbs et al., 2006a). Our results show a distinct difference between the late Paleocene and recovery to post excursion intervals that cannot be explained by a long-term shift in environment. Instead, it appears that nannoplankton taxa adapted to changing conditions across the PETM and retained their ecologies into the Eocene.

The change in the community seen at the PETM may have implications for the adaptation of modern nannoplankton in rapidly changing ocean habitats. It is projected that in coming decades calcareous nannoplankton will become more abundant in areas typically dominated by diatoms (Cermeño et al., 2008), similar to the expansion of warm water taxa into high latitudes during the PETM (Bralower, 2002). However, our results show the response of nannoplankton at the PETM was considerably more complicated than a global increase in warm-water oligotrophs. Rather, reorganization of the nannoplankton community appears to be driven by interactions between species as a result of temperature and nutrient changes; such interactions are difficult to predict based on assumed temperature and nutrient-level changes. Climatic changes could cause a restructuring of nannoplankton communities in coming years that may have a lasting impact. This has implications for oceanic primary productivity, biological pumping and the carbon cycle in the future.

#### CONCLUSIONS

In this study we examined the longer-term effects of transient warming on nannoplankton populations during the PETM. By using multivariate ordinations with temperature proxies and

modeling results, we are able to provide quantitative paleoecologies for nannoplankton as opposed to inferring ecology from biogeographic distributions. Using these methods we find that Shatsky Rise and Walvis Ridge responded more to a change in nutrient availability than to temperature change. Alternatively, temperature had a greater impact on the assemblages of Maud Rise and Demerara Rise. The largest change in nannoplankton assemblages occurred along shelves and in high latitudes. The results of the model simulation provide supporting evidence that the open ocean became more stratified and less productive during the PETM. These results paired with existing temperature proxies can be used to distinguish between nutrient and temperature effects on nannoplankton assemblages, two variables that are often entangled. The cluster analysis plots show a distinctive shift in nannoplankton communities caused by the PETM. It appears that nannoplankton taxa adapted to warming conditions and these ecological modifications persisted past the CIE.

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**Figure 2.1**. Paleoreconstruction map of the globe at 55 Ma (www.odsn.de) showing the PETM localities: Maud Rise (Site 690), Shatsky Rise (1209), Demerara Rise (Site 1260), Walvis Ridge (Site1263), Forada, Italy, and Wilson Lake and Bass River (WL/BR), New Jersey, USA.



**Figure 2.2**. Cluster analysis of the entire global data set. Genera break out into two main groups: open ocean and shelf-hemipelagic taxa, which in turn can be further subdivided. These descriptions are based upon the overall paleoecological affinities of the genera included within the grouping (see Table 2.1).



**Figure 2.3.** Cluster analyses for the five time divisions across the PETM. Ages are relative to the onset of the PETM. Each group is color-coded based upon the interpreted ecological affinities of the taxa.



**Figure 2.4**. DCA plots showing (a) samples and (b) genera across the PETM for 7 different sites. Arrows indicate the stratigraphic trends across the PETM. The groupings in 4b are color-coded to match the clusters in Figure 2.2.



**Figure 2.5.** Results from the GENIE model of Cui et al. (2011). Displayed are biological PO<sub>4</sub> uptake, the planktonic-benthic PO<sub>4</sub> gradient, and the planktonic-benthic temperature gradient. Time is measured as years above the onset of the PETM.



**Figure 2.6.** Global DCA plot with productivity and temperature changes as indicated by proxies other than nannofossil assemblages and GENIE model results. Panel a) displays productivity trends as identified by proxies. The New Jersey coast shows increased productivity at the PETM based upon sedimentation rates (Cramer et al., 1999; John et al., 2008) and the dinoflagellate assemblage (Sluijs and Brinkhuis, 2009). Forada has been interpreted as having increased productivity based upon sedimentation rates (Bains et al., 2000) and increased Sr/Ca ratios in coccoliths (Stoll et al., 2007) indicating enhance productivity. Coccolith Sr/Ca shows no change at Demerara Rise and Shatsky Rise (Stoll et al., 2007). Panel b) displays surface water temperatures (°C) before and during the PETM as determined by proxies (see Figure 2.5 caption for references). Panel c) displays modeling values of biological PO<sub>4</sub> uptake (10<sup>-7</sup> mol kg<sup>-1</sup> yr<sup>-1</sup>) before and during the PETM. Panel d) shows temperatures (°C) derived from the GENIE model before and during the PETM. DCA axis 1 can be interpreted as a temperature gradient and DCA axis 2 as a productivity gradient.



**Figure 2.7.** GENIE model output of global export POC (mol/yr), which is an indicator of productivity. Time is measured above the onset of the PETM.



**Table 2.1.** Past interpretations of paleoecologies for nannoplankton genera compared to this study.

	Warm	Temperate	Cool	Oligotrophi	c Meso/eutrophi	ic This Study
Biscutum					5, 9, 18, 19	Cool, mesotrophic
Ericsonia	3, 5, 7, 14, 15, 20, 21, 24, 23, 25			5,21,23		Warm, tolerant of wide nutrient range
Chiasmolithus			3, 5, 7, 10, 17, 20, 21, 22, 23, 24, 25		3 4 5 15 16 2	21 Cool mesotrophic
Zvarhablithus	5 13	20.23	21,22,20,21,20	4 5 13 24	6 21 23	Cool, mesotrophic in late Paleocene; more broadly adapted in early Eocene
Lygi habitilus	5,15	20,25	<i>L</i> :	4,5,15,24	0,21,25	Locene
Prinsius			5,12		5,12	Cool, mesotrophic
Campylosphaera	16				11,16	Warm, tolerant of wide nutrient range
Discoaster	3, 5, 7, 8, 11, 13, 14, 20, 21, 23, 25			3,4,5,8,11, 13,14,15,21		Warm, oligotrophic
Sphenolithus	1, 5, 5, 11, 12, 15, 20, 21, 22, 23, 24, 25			1,5,11,23		Warm, oligotrophic
Fasciculithus	5,12,24				5	Warm, oligotrophic
Cocclithus	24	17,22,23				Ubiquitous
Toweius			5, 11, 12, 21		5,11,21	Ubiquitous
Rhomboaster	4				4	Excursion taxa?
Calciosolenia, Zygodiscus, Zeugrhabdotus, Hornibrookina						Warm, meso- to eutrophic
Coronocyclus, Neochiastozygus, Cruciplacolithus, Ellipsolithus, Neococcolithes, Pontosphaera						Meso- to eutrophic, low

Agnini et al. (2006); 2 Agnini et al. (2007); 3 Aubry, (1992); 4 Aubry (1998); 5 Bralower (2002); 6 Bralower and Kalb (in review); 7 Bukry (1973);
Edwards (1968); 9 Erba et al. (1992); 10 Firth and Wise (1992); 11 Gibbs et al. (2006); 12 Haq and Lohmann (1976); 13 Kahn and Aubry (2004);
14 Kelly et al. (1996); 15 Monechi et al. (2000); 16 Mutterlose et al. (2007); 17 Persico and Villa (2004); 18 Roth and Bowdler (1981);
19 Roth and Krumbach (1986); 20 Schneider et al. (2011); 21 Tremolada and Bralower (2004); 22 Villa and Persico (2006); 23 Villa et al. (2008);
24 Wei and Wise (1990); 25 Wei et al. (1992)

# CHAPTER 3: ENHANCED CALCAREOUS NANNOPLANKTON PRODUCTIVITY DURING THE MIDDLE MIOCENE TRANSITION IN THE EASTERN EQUATORIAL PACIFIC (IODP SITE U1338)

# ABSTRACT

The middle Miocene transition (MMT; 13.9 Ma) marks the major expansion of the East Antarctic ice sheet (EAIS) as well as a significant cooling of high latitudes. This event is tied to enhanced bottom water formation and cooling high latitude regions; however, little is known about its effect on low latitude climate and oceanography. To better understand the relationship between glaciation and equatorial upwelling, we use the nannoplankton assemblage from IODP Site U1338 (eastern equatorial Pacific) as an indicator of temperature and productivity change. We see a change in the nannoplankton assemblage associated with the MMT and carbon isotope maximum 6 (CM6). At the MMT, warmer-water taxa decrease in abundance and there is an increase in the cool-water species Dictyococcites antarcticus and Sphenolithus abies. During CM6, which is coincident with the maximum in glaciation, there is a significant increase in very small *Dictyococcites* species that have a bloom-like quality. In the modern ocean, this type of assemblage would be found in a highly productive setting. After CM6 the assemblage returns to abundance values similar to the pre-MMT interval. We interpret the assemblage shifts as showing an increase in productivity during the MMT and CM6. Because the nannoplankton changes are concurrent with EAIS expansion as indicated by benthic isotopes, this is evidence that glaciation caused an increase in equatorial upwelling. Major glaciation has the potential to influence equatorial upwelling through enhanced wind patterns or greater nutrient supply to the thermocline.

#### **INTRODUCTION**

The middle Miocene was a period of rapid and significant climatic changes. The middle Miocene transition (MMT; 13.9 Ma) marks the major expansion of the East Antarctic ice sheet (EAIS; Shackleton and Kennett, 1975; Wright et al., 1992; Flower and Kennett, 1993) and is the culmination of a ~800 kyr cooling trend following the end of the Miocene climatic optimum (MCO; ~17 to 14.7 Ma; Figure 3.1). The MMT is considered to be the final Cenozoic shift from a greenhouse world into a modern-day-like ocean-atmospheric system with cold high latitudes and a strong meridional temperature gradient (Vincent and Berger, 1985). Atmospheric  $pCO_2$  proxies from this time vary; one scenario shows concentrations decreasing from 300-580 ppm at the MCO to 140-280 ppm following the MMT (Pearson and Palmer, 2000; Kürschner et al., 2008; You et al., 2009), while another shows no change at all (Pagani et al., 1999).

The MMT is characterized by a 1‰ increase in benthic foraminiferal  $\delta^{18}$ O values and records the Mi-3 glaciation (Shackleton and Kennett, 1975; Vincent and Killingley, 1984). Approximately 85% of the  $\delta^{18}$ O excursion is attributed to increased ice volume on Antarctica (Lear et al., 2000; Langebroek et al., 2010). This increase in ice volume occurred over the course of two obliquity cycles (~80 kyr; Holbourn et al., 2005). A decline in *p*CO<sub>2</sub> and changes in ocean circulation have been invoked as cooling mechanisms but both are poorly constrained (Woodruff and Savin, 1989; Pearson and Palmer, 2000; Kürschner et al., 2008). Holbourn et al. (2005) proposed that the EAIS expansion occurred during an interval of low-amplitude variations in obliquity and a decrease in eccentricity and proposed that these forcings resulted in low insolation over Antarctica favoring ice growth. This glacial period had an impact on the biota as well; major changes traced to EAIS expansion include migrations in forest types (e.g. Wolfe, 1985), expansion of C<sub>4</sub> grasses (Edwards et al., 2010), and a turnover in planktonic foraminifera (Wei and Kennett, 1986; Figure 3.1).

The MMT is within the Monterey Excursion interval, an event that is defined by a ~1‰ positive  $\delta^{13}$ C shift in global benthic foraminiferal records at ~17 Ma that persists for over 3 my (Vincent and Berger, 1985; Figure 3.1). The Monterey Excursion was hypothesized to be the result of enhanced oceanic productivity, as evidenced by the organic and phosphate-rich deposits found along coastal margins such as the Monterey Formation (e.g. Vincent and Berger, 1985; Mallinson and Compton, 1997). More recently, this idea of enhanced oceanic productivity as the cause of the  $\delta^{13}$ C excursion has been contested in favor of continental carbon burial (Föllmi et al., 2005; Diester-Haass et al., 2009). The Monterey Excursion is composed of 6-7 carbon isotope maxima (CM; Woodruff and Savin, 1991), the largest of which, CM6, coincides with the peak of Mi-3 glaciation (Shevenell et al., 2004). Flower and Kennett (1993) linked the two events by suggesting that there was increased C<sub>org</sub> burial during cooler intervals with lower sealevel; alternatively, Holbourn et al (2005) argue that it reflects increased carbon storage because of a depressed calcite compensation depth (CCD).

The surface and benthic records show that there was a significant evolution in the waters around Antarctica. Southern Ocean sea surface temperatures decreased 7°C in the time leading up to the MMT, with  $\sim$ 2°C of that cooling occurring during the oxygen isotope shift (Shevenell

et al., 2004). The benthic temperatures also decreased by 2°C with large (~5°C) oscillations as determined by Mg/Ca records (Shevenell et al., 2008). Changes in  $\delta^{13}$ C values indicate that Southern Component Water (SCW) intensified after the MCO, and became strong at the MMT (Wright et al., 1992; Flower and Kennett, 1995).

The changes in deep ocean circulation accompanying Mi-3 could have had far reaching effects on other parts of the ocean. In the modern ocean, the formation of intermediate water in the Southern Ocean has been shown to supply nutrients to the thermocline in low latitudes (Sarmiento et al., 2004). Similarly, intensification in the production rate of these waters in Mi-3 could have led to an increase in the supply of nutrients. Furthermore, it has been documented that during the Pleistocene, upwelling in the Eastern Equatorial Pacific (EEP) was linked to high latitude forcing (Liu and Herbert, 2004). The increase in meridional temperature gradients associated with high latitude cooling would have strengthened wind patterns and intensified upwelling (e.g. Vincent and Berger, 1985).

Calcareous nannoplankton have a significant role in the carbon and carbonate cycles (Hay, 2004) and are one of the most prolific primary producers in the modern ocean (Westbroek et al., 1993). Their distribution is determined by environmental factors, primarily sea surface temperature and nutrient concentrations. As such, their fossils are useful for studying intervals of climate change because they track changes in temperature and primary production. The calcareous nannofossil record from the Miocene is robust and the biostratigraphy is well established (e.g. Gartner, 1992; Fornaciari et al., 1996; Raffi et al., 2006), but assemblage studies are exceedingly rare. Nannoplankton assemblage studies have the potential to determine whether the MMT and Mi-3 glaciation impacted areas other than the Southern Ocean.

Through combining nannofossil assemblage counts and geochemical records, this study seeks to understand how nannoplankton populations were affected by the Mi-3 glaciation, if there was increased production in the EEP during CM6, and if EEP productivity was linked to high-latitude forcing.

# **METHODS**

Samples were obtained from the composite section (CCSF-A) of Site U1338. This site was drilled by the PEAT expeditions (IODP Exp 320 and 321) and is located in the Eastern Equatorial Pacific at a water depth of 4200 m (Figure 3.2). Now located at 2°30.469' N,
117°58.178'W, paleolatitude estimates place U1338 to  $\pm 2^{\circ}$  of the equator during the middle Miocene (Expedition 320/321 Scientists, 2010). Samples were taken at 20-30 cm interval from 354-391 CCSF-A (m). The sediment is primarily nannofossil ooze and chalk (Expedition 320/321 Scientists, 2010).

Smear slides for nannofossil counts were prepared using the double slurry method of Watkins and Bergen (2003). Certain taxa were either split up or placed together based upon morphology. *Reticulofenestra* taxa are divided by size in the Miocene (Backman, 1980). *Reticulofenestra minuta* is less than 3  $\mu$ m in size, *R. haqii* is between 3 and 5  $\mu$ m, and *R. pseudoumbilicus* is greater than 5  $\mu$ m. *Reticulofenestra pseudoumbilicus* was further divided by size for this study, separating out the individuals between 5 and 7 $\mu$ m from those greater than 7  $\mu$ m. *Dictyococcites* species were treated in a similar manner and were divided into *Dictyococcites* < 3 $\mu$ m, *D. antarcticus* 3-5  $\mu$ m, and *D. antarcticus* > 5  $\mu$ m. The size fraction < 3  $\mu$ m is not referred to as *D. productus* because that species is documented as originating in the Pliocene (Backman, 1980). *Sphenolithus moriformis* and *S. compactus* are grouped in the percent abundances because it is often difficult to discriminate between the two species as *S. compactus* considered to be a smaller version of *S. moriformis* (Backman, 1980). See Plates 3.1 and 3.2 as a visual reference for our taxonomic concepts.

Nannofossil individuals were counted until 300 individuals, not including specimens less than 3  $\mu$ m in size and 3-5  $\mu$ m *Dictyococcites antarcticus*, were reached (here termed the small nannofossil species; SNS). This strategy was implemented because the 3-5  $\mu$ m size fraction of *D*. *antarcticus* is very abundant in some samples and we wanted to get a representation of the rest of the assemblage. In addition, the abundance of small (< 3 $\mu$ m) specimens could be strongly impacted by preservation as smaller fossils have a higher surface area to volume ratio (Hill, 1975). The SNS were counted and totaled, but not included in the 300-specimen limit (Table B.1). The counts were then converted to percent abundance. The 3-5  $\mu$ m *D. antarcticus* fraction is included in the total percent abundances.

Richness (S) and Shannon-Wiener diversity (H) indices were calculated using the program R (www.r-project.org) from the nannofossil percent abundances. Evenness (J) for samples was calculated using the relationship J=H/(log S). Specimens less than  $3\mu m$  in size were not included in these analyses. These metrics can give some indication of the environment. For

instance, in high productivity regions, richness, diversity, and evenness of nannoplankton is often low.

Nannofossil percent abundance data were analyzed statistically using multivariate analyses in R. Nannofossil percents were combined into a matrix. Species or genera composing less than 2% of the assemblage were omitted because rare species tend to form outliers. A square-root transformation was applied to the matrix to decrease the influence of dominant taxa. A cluster analysis was performed on the samples to determine the hierarchical groupings of species. The cluster analysis used the Sørensen (Bray-Curtis) distance metric with Ward's method as the linkage method.

A detrended correspondence analysis (DCA) was chosen as an ordination technique, using the Bray-Curtis distance metric. DCA was calculated using the 'decorana' function in R. DCA ordinates species and sample simultaneously and the plots display samples and species along a gradient that can subsequently be interpreted. The distance between samples is a gauge of the relative similarity of dissimilarity of taxa within those samples. Species plot near the samples they are most frequently found in. DCA assumes modal species distributions along a gradient (Peet et al., 1988). The 'envfit' function was used to correlate opal wt.% to the DCA ordination results.

The grain size distribution was determined using the Malvern Mastersizer at the Materials Research Laboratory at Penn State University. Unprocessed sediment was placed into a small vial with distilled water and sonicated for  $\sim$ 5 minutes before being injected into the Mastersizer. Particles between 0 and 1000 µm were measured, but the majority of sizes ranged between 0 and 100 µm.

The age model adopted was constructed using the astronomically calibrated age for the last occurrence (LO) of *Sphenolithus heteromorphus* (13.53 Ma; Lourens et al., 2004), which was determined to within 10 cm (362.47 m CCSF-A), and assuming a constant sedimentation rate of 28.7 m/my (Expedition 320/321 Scientists, 2010). The LO of *S. heteromorphus* marks the top of nannofossil zone NN5 (Martini, 1971).

These data are compared to the estimated CaCO<sub>3</sub>% curve generated from XRF core scanning (Lyle et al., in review), opal weight percent (O. Romero, unpublished data), and benthic foraminifera  $\delta^{18}$ O and  $\delta^{13}$ C records (2 point moving average; A. Holbourn, unpublished data).

## RESULTS

The geochemical records display large variations throughout the early-middle Miocene interval. The estimated  $CaCO_3\%$  curve of Lyle et al. (in review) is centered around ~80% with two large decreases at 371 m and 376 m (Figure 3.3). The decreases in  $CaCO_3\%$  are matched by increases in the opal weight percent record (Figure 3.3). Opal wt.% is typically less than 5% throughout the study interval, but increases to between 25 and 40% from 374-378 m. There is a secondary peak from 368-371 m. Both radiolarians and diatoms compose the opal fraction, but from smear slide observations, diatoms are the dominant opal component. The opal wt.% and estimated  $CaCO_3\%$  from the XRF scanning account for almost the entirety of the sediment composition. This indicates that the decrease in the carbonate record is not due to dissolution, but rather dilution by silica and increased siliceous productivity.

The benthic  $\delta^{18}$ O curve has both small and large variations (Figure 3.3). The smaller fluctuations found between 378 m and 373 m have been shown to be obliquity-paced at other sites (Holbourn et al., 2005). The main isotope shift of 0.9‰, marking the Mi-3 glaciation, occurs between 368-373 m. Following the MMT is CM6, the timing of which is determined by benthic  $\delta^{13}$ C records (A. Holbourn, unpublished data).

The  $\delta^{13}$ C values increase by ~0.6‰ from ~373 to 367 m (Figure 3.3). CM6 spans the interval after the MMT between 359 and 368 m. The termination of CM6 at 359 m marks the end of the Monterey excursion.

The smear slides indicate that nannofossil preservation is good overall, with little overgrowth and etching between E-1 and E-2 on the scale of Roth and Thierstein (1972). The species richness, evenness, and Shannon diversity display similar trends through the section (Figure 3.4). The species richness varies between 13 and 24 species found in a sample, with a mean value of 17.5 species/slide. The evenness values are between 1.29 and 1.87 with a mean of 1.59. The Shannon diversity ranges from 1.59 to 2.5 with a mean of 1.97. For each of the curves, the same trend through time is present: a notable increase in values starting around 382m and reaching a maximum at ~380 m. From this point, the curves show a decreasing trend with a local minimum at 366 m. The decreasing trend ends at 359 m (coinciding with the end of CM6) and the values either stay about the same or increase.

The nannofossil abundances vary dramatically over the study interval. In the interval leading up to the silica maximum (377-391 m), there are several peaks in abundance (Figure

3.5a,b). Notably there are significant increases in *Coccolithus pelagicus, Coccolithus miopelagicus*, and *R. haqii*; this interval also has a large abundance of *D. antarcticus* 3-5 μm. The abundances of *Cyclicargolithus floridanus, Discoaster*, and *Helicosphaera* are variable, but can be quite high in samples.

During the silica peak interval (374.5-377 m), there is an increase in the abundances of *C*. *floridanus, C. pelagicus, Discoaster, D. antarcticus* >5  $\mu$ m, and *R. pseudoumbilicus* 5-7  $\mu$ m. This is matched by decreases in the abundances of *Helicosphaera, R. pseudoumbilicus* >7  $\mu$ m, *D. antarcticus* 3-5  $\mu$ m, and *Sphenolithus heteromorphus* (Figure 3.5).

At the MMT interval (368-373 m), there is an increase in the total *Dictyococcites* %, *D. antarcticus* >5  $\mu$ m, *Sphenolithus abies*, and a peak in total *Sphenolithus* (Figure 3.4b). There is sharp peak in *Discoaster* in the middle of this time span. The increase in *Dictyococcites* species is sustained through the CM6 interval (359.5-368 m) and dominates the assemblage. *Sphenolithus abies* becomes the main form of this genus with the dramatic decline of *S. heteromorphus* at CM6. The larger forms of *Reticulofenestra* (>5  $\mu$ m) have high abundances. *Cyclicargolithus floridanus* and *Discoaster* make up a very small percentage of the population and *Helicosphaera* has a large abundance peak in this interval. During CM6 this is a large increase in the number of *Dictyococcites* specimens less than 3  $\mu$ m in size that lasts for almost the entire duration (Figure 3.3).

The interval above CM6 (354.5-359.5 m) contains an increase in the abundances of *C*. *miopelagicus, C. pelagicus, R. haqii, Discoaster, Helicosphaera*, and *D. antarcticus* 3-5  $\mu$ m. There is a decrease in *Sphenolithus moriformis/compactus*, total *Reticulofenestra*, large (>5  $\mu$ m) forms of *Reticulofenestra*, and the number of *Dictyococcites* <3  $\mu$ m.

The cluster analysis divides the taxa based upon how similar their distributions are among the samples (Figure 3.6). The first main clustering contains *Calcidiscus, Helicosphaera, S. compactus/moriformis, C. miopelagicus, C. floridanus, Discoaster*, and *Umbilicosphaera*. The other main grouping contains *C. pelagicus, S. heteromorphus, S. abies*, and the *Reticulofenestra* and *Dictyococcites* species.

DCA axes 1 and 2 display the most variance in the data set. DCA 1 accounts for 55.7% of the variance in the dataset and DCA 2 shows 15.2% of the variance. Samples have DCA 1 values ranging from -0.5 to 0.5 and DCA 2 values from -0.4 to 0.5 (Figure 3.7). The species values range from -2.5 to 2 along DCA 1 and from -2 to 2 (Figure 3.8). Samples are divided into time

slices: pre-glaciation (373-391 m), opal peak (374.5-378 m), the MMT (368-373 m), CM6 (359-368 m), and post-glaciation (354-359 m).

The envfit function produced a correlation of  $r^2=0.623$  between the ordination and opal wt. %. The vector of the envfit indicates the direction of the highest opal concentrations on the ordination (Figure 3.7).

The grain size analyses show a bimodal distribution in the samples. The primary peak falls in the size range of 2 and 6  $\mu$ m (Figure 3.3, warm colors). The secondary peak is much less abundant than the first and ranges from 20-50  $\mu$ m. The frequency of the large size fractions increases during intervals with higher opal wt.%. The typical size of nannofossils is between 2-20  $\mu$ m. The range of diatoms is larger, between 2 and 200  $\mu$ m. Because of the larger size fraction is associated with increases in opal wt.%, this peak likely represents the portion of the sediment that is composed of diatom frustules and the majority of the sediment is made of nannofossils.

## DISCUSSION

## The middle Miocene transition

The benthic isotope record can be used to link high latitude ice sheet growth to productivity in the EEP. The fluctuations in the benthic  $\delta^{18}$ O curve are believe to be derived from ice sheet oscillations driven by obliquity (Holbourn et al., 2005) and the 0.9‰ positive shift marks the major expansion of ice sheets (e.g. Shackleton and Kennett, 1975; Wright et al., 1992; Flower and Kennett, 1993). The benthic  $\delta^{18}$ O record from Site U1338 shows these same trends (Figure 3.3). By comparing the timing of shifts in the nannoplankton assemblage to the  $\delta^{18}$ O record, a direct link to changes in EEP upwelling intensity and Antarctic glaciation can be made.

Overall, the nannofossil assemblage at Site U1338 is quite different from that found in the North Pacific tropical gyre. The warm water, oligotrophic assemblages from the North Pacific Shatsky Rise contain abundant *C. floridanus*, common *Discoaster, Reticulofenestra*, and *C. pelagicus* were common, *Sphenolithus* was rare, and there were no *Helicosphaera* or *Dictyococcites* present (Bown, 2005b).

The cluster analysis splits taxa by abundances and ecologies. The upper cluster is composed of taxa that have smaller abundances than the bottom cluster (Figure 3.6). The upper cluster is sub-divided into two groupings. The first group experienced little change in abundance across the MMT and includes *Calcidiscus, Helicosphaera*, and *S. compactus/moriformis*. The

second sub-division includes *C. miopelagicus, C. floridanus, Discoaster*, and *Umbilicosphaera*, warm water to temperate taxa as discussed above. The bottom cluster is also split into two groups. The first group is interpreted as a lower productivity regime and includes *C. pelagicus, R. haqii*, and *S. heteromorphus*. The second group is composed of higher productivity taxa such as *Dictyococcites* spp., *R. pseudoumbilicus*, and *S. abies*.

At the MMT, there was a change from a warmer-water, less productive assemblage to a higher productivity assemblage. Prior to the MMT, the assemblage was composed of warmer and more temperate forms (Figures 3.5, 3.6): *C. floridanus* (Haq, 1980), *C. pelagicus* (Haq, 1980; Bown, 2005), and *Discoaster* (e.g. Bukry, 1973; Aubry, 1992). In addition, a large portion of the assemblage was composed of *Reticulofenestra*, a genus having higher abundances in cooler, more productive localities, but also found throughout the world ocean (e.g. Haq, 1980; Bown, 2005). At the MMT there was an abrupt increase in total *Dictyococcites, D. antarcticus* >5 µm, and *Sphenolithus abies* (Figure 3.5). *Dictyococcites antarcticus* is described from the Southern Ocean (Haq, 1976) and it was primarily distributed in high southern latitudes. It has also been described in the Mediterranean (Wade and Bown, 2006) and the North Atlantic (Sblendorio-Levy and Howe, 1998). Typically, *Sphenolithus* is thought to have been a warm water, oligotrophic genus (Haq and Lohmann, 1976; Wei and Wise, 1990; Aubry, 1992), but its high abundance in the EEP suggests it was well adapted to higher-nutrient settings. During the Miocene, *Sphenolithus abies* in particular was found in unique and extreme environments such as the Mediterranean during the Messinian Salinity Crisis (Wade and Bown, 2006).

Other changes at the MMT are a drop in diversity and an increase in opal content. There is a decline in diversity across the MMT, which also supports the interpretation of a more productive regime (Figure 3.4). Nannoplankton diversity is highest in warm, oligotrophic environments and declines with increased production and lower salinity (Baumann et al., 2005). Opal content increases during the MMT up to 20% (Figure 3.3). This increase is indicative of enhanced diatom production in surface water due to increased upwelling. However, the distribution of diatoms during the study interval is probably due to silica limitation as discussed below. The increase in mesotrophic-eutrophic taxa at the MMT, a decrease in nannofossil diversity, and a slight increase in opal wt.% suggest that there was cooler water and increased nutrient supply in the EEP. Around the time of the MMT, but not well correlated to the benthic  $\delta^{18}$ O record, is an increase in the coccolith size of *Reticulofenestra* (Figure 3.5). There is an increase in larger forms (5-7 µm and >7 µm size) beginning around the time of the increase in silica at ~377 m. During the Miocene there is an increase in the coccolith size of *R. pseudoumbilicus* (Young, 1990). Young (1990) documents an evolutionary trend towards larger sizes of *R. pseudoumbilicus* from nannofossil zone NN6 to NN10 in the Indian Ocean. Young's (1990) study interval post-dates the MMT, which occurs in nannofossil zone NN5.

The division of *Reticulofenestra* species based upon size is arbitrary and may not represent different species (Backman, 1980). However, size and calcification can be indicative of environment. For instance, the more calcified form of *R. pseudoumbilicus*, termed *R. gelida*, is found in cool waters and may be an ecological variant of *R. pseudoumbilicus* (Backman, 1980). Modern morphotypes of *Calcidiscus leptoporus* display seasonal variations in size, with size decreasing with increasing temperature (Renaud et al., 2002). These examples demonstrate that size variations within a nannoplankton species can be driven by environment.

If the size change seen in *Reticulofenestra* during the middle Miocene were solely evolutionary, it would be expected that the size distribution in our samples would trend from *R*. *haqii* size towards *R*. *pseudoumbilicus* >7  $\mu$ m through time. However, the abundance of *R*. *haqii* remains almost constant throughout the MMT and CM6 and the larger forms of *R*. *pseudoumbilicus* have higher abundances during the same interval (Figure 3.5). This suggests that the size trends observed are likely a combination of ecology and evolution.

#### Carbon isotope maximum 6

East Antarctic glaciation reached a maximum volume during CM6 (Shevenell et al., 2004). This interval is correlated to an organic-rich section of the Monterey Formation (Flower and Kennett, 1994), leading to the interpretation that the Monterey carbon isotope excursion was caused by an increase in oceanic productivity (e.g. Vincent and Killingley, 1994). The nannofossil assemblage at Site U1338 is dominated by high productivity taxa *Dictyococcites, Reticulofenestra*, and *S. abies* during CM6 and diversity reaches a low for the entire study section (Figure 3.4, 3.5, 3.6). The assemblage is similar to that of the MMT, but has a comparably high abundance of total *Dictyococcites* and large forms of *Reticulofenestra* (Figure 3.5). The most drastic change in the assemblage is the abrupt increase in small (<3 µm)

*Dictyococcites* (Figure 3.3). These small individuals appear to be bloom-like based upon smear slide observations. In the modern ocean, similar, small placolith forms are associated with high productivity (e.g. Winter et al., 1994). The presence of these small forms is not the result of preservation; other fossil specimens appear no more or less etched than in other parts of the section. In some samples, *Dictyococcites* < 3  $\mu$ m numbered over 1000 compared to the other 300 specimens counted. If the small *Dictyococcites* were included in the percent abundances or the diversity indices, there would be a significant decrease across the board and the percentages of all of the other taxa would be dwarfed. The large increase in these smaller forms denotes a further increase in productivity during CM6 from the MMT.

Coincident with the end of the MMT is a decline in the population of *S. heteromorphus* up until its extinction (Figure 3.5). It is unclear if climatic changes led to the final extinction of this species or only contributed to its localized decline in abundance. A similar decline in abundance of the species before the extinction is seen in the Mediterranean (Fornaciari et al., 1996). The only way to determine if EAIS expansion contributed to the demise of *S. heteromorphus* globally would be to accurately correlate the abundance decrease at multiple localities.

At the end of the Monterey excursion (CM6), there is an increase in the abundance of warmer water taxa, similar to the assemblage prior to the MMT. *Coccolithus miopelagicus, C. pelagicus*, and *Discoaster* all increase in abundance (Figure 3.5a). The total *Dictyococcites* and *S. abies* abundances do not change from CM6, while *R. pseudoumbilicus* declines (Figure 3.5b). The number of *Dictyococcites* <3  $\mu$ m drops rapidly at 361 m, before the end of CM6. This is interpreted as a warmer water, less productive assemblage.

The time interval following CM6 (13.5-13.3 Ma) had relatively warm bottom waters and Mg/Ca records from benthic foraminifera suggest no permanent cooling following the Mi-3 glaciation (Shevenell et al., 2008). This evidence strengthens our interpretation of a less productive assemblage in the EEP at this time.

## **Diatom production**

In the modern ocean, diatoms are present in areas that have high nutrient input and cool waters, primarily equatorial and low latitude coastal upwelling regions, and the Southern Ocean (e.g. Cortese et al., 2004). Today the EEP is a high nitrate, low chlorophyll zone that is silica-

and iron-limited for diatoms (Dugdale and Wilkerson, 1998). From a physiological standpoint, nutrient availability is particularly important as diatoms require more phosphate and nitrate input than nannoplankton owing to their relatively low surface area to volume ratio and high growth rates (Sarthou et al., 2005). It is expected that diatom abundance would peak in the section with the highest productivity, CM6. However, opal wt.% peaks well before CM6 at 374.5-378 m (Figure 3.3). The time period from 14.1-14.5 Ma was a relatively warm interval in the Southern Ocean based upon the benthic temperatures (Shevenell et al., 2008). Starting at ~14.1 Ma, around the start of the opal peak, both SSTs and benthic temperatures in the high southern latitudes began to cool (Shevenell et al., 2004; 2008). It is during this interval that nannofossil diversity is at its highest, suggesting relatively warmer, lower nutrient conditions (Baumann et al., 2005; Figure 3.4).

During the primary opal peak interval (374.5-378 m), opal wt.% shows an inverse trend to the benthic  $\delta^{18}$ O record (Figure 3.9). Opal wt.% is highest when  $\delta^{18}$ O values are low, interpreted as a result of waning ice sheet volume. Similarly, the warmer water taxa of this study, *Discoaster* and *Reticulofenestra* appear to have the same relation to the  $\delta^{18}$ O record. *Sphenolithus* and *Helicosphaera*, which is typically found in upwelling zones (Perch-Nielsen, 1985), tend to show a direct relationship to the  $\delta^{18}$ O record. Based upon the nannofossil abundance patterns, there was an increase in productivity when ice sheet volume increased. This link between opal wt.% and warm water taxa is also seen during the increase in opal wt.% during the MMT. In this section the samples with greater opal content also have a greater number of *Discoaster* specimens (Figure 3.3, 3.5a). The increase in opal content occurred during a less productive interval for calcareous organisms. This suggests that silica limitation prevented diatoms from living in the equatorial Pacific during CM6.

In the middle Miocene, silica deposition changed from the Atlantic to the North Pacific basin in what has been termed the "silica switch" (Keller and Barron, 1983: Woodruff and Savin, 1989; Barron and Baldauf, 1990; Cortese et al., 2004). The "silica switch" is believed to be the result of changes in bottom water circulation, primarily intensification of North Atlantic Deep Water (NADW) formation (Keller and Barron, 1983). This "silica switch" is found at ~310 m at Site U1338 (Lyle et al., in review), marking the time in the EEP when bottom waters were no longer corrosive to silica deposition and there was correspondingly increased siliceous productivity in the surface waters.

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If during the middle Miocene, the thermocline waters supplying the nutrients to the EEP were also silica depleted, it would prevent diatoms from flourishing in this environment. In the modern ocean, Subantarctic Mode Water (SAMW) supplies approximately half of the nitrate to the equatorial Pacific, but only ~30% of silica (Dugdale et al., 2002; Sarmiento et al., 2004). The majority of the silica transported to the equatorial Pacific comes from North Pacific Intermediate Water (NPIW; Sarmiento et al., 2004). Sarmiento et al. (2004) proposed that vertical mixing in the North Pacific transports nutrients from North Pacific Deep Water (NPDW) up into NPIW, where it then feeds the equatorial Pacific. Ultimately, the supply of silica to the equatorial Pacific is contingent upon the amount contained in the bottom waters and the presence of siliceous organisms.

The opal peak observed in this study section maybe the result of a brief change in circulation, such as a pulse of intensified North Atlantic Deep Water (NADW) formation. The peaks of opal coinciding with troughs in the  $\delta^{18}$ O record could reflect intervals when older water masses invaded the Pacific (Figure 3.9). During intervals of increased ice sheet volume, represented by peaks in the  $\delta^{18}$ O record, there may have been intensification of downwelling in the Southern Ocean that blocked the influx of NADW into the Pacific basin.

## Long-term nannoplankton changes in the eastern equatorial Pacific

The Mi-3 glaciation had a long-term impact on nannoplankton assemblages in the EEP. Prior to the glaciation interval, *Reticulofenestra* abundance ranged from ~20-30% of the assemblage (Figure 3.5). Across the glacial period, *Reticulofenestra* abundance decreased to ~10-20% and the *Dictyococcites* percentage increased and remained elevated after CM6. Kameo and Sato (2000) found the same trend at EEP sites: in the early middle Miocene the assemblage had a large percentage of reticulofenestrids and by the middle middle Miocene, *Dictyococcites* became dominant. *Dictyococcites* remained prevalent in the EEP to the late Miocene (Kameo and Sato, 2000). This suggests that either the glaciation continued to influence upwelling to some degree after Mi-3 or these environmental shifts allowed for certain taxa to permanently displace others.

The NMS ordination confirms these observations of a long-term impact on the nannoplankton assemblage. Pre-glacial samples have positive NMS 1 values and are divided from the MMT, CM6, and post-glacial samples, which have negative NMS 1 values (Figure 3.7).

The taxa from the warm-temperate water and lower productivity clusters plot near the pre-glacial samples (Figures 3.6, 3.7, 3.8). The high productivity species cluster plot near the CM6 samples. The division of samples along NMS 1 through time reflects a change from a *R.haqii*, *C. pelagicus*, *S. heteromorphus* assemblage to a *Dictyococcites*-dominated assemblage. We interpret this as a shift from a warmer, less productive regime to a high productivity regime. Despite the increase in warm-temperate species during the post-glacial interval (Figure 3.5a), these samples plot closely with the CM6 samples (Figure 3.7). This could either reflect the high abundance of *Dictyococcites* in all of these samples and/or no change in productivity from CM6 to the post-glaciation interval. Because of the decline of  $< 3 \, \mu m$  *Dictyococcites* at the end of CM6, it is unlikely that productivity did not change after CM6. The MMT caused a change in nannoplankton assemblage through an increase in *Dictyococcites*.

## High latitude forcing on equatorial Pacific upwelling

In other times of the geologic past, upwelling changes in the EEP have been linked to high latitude forcing. For example, Liu and Herbert (2004) used the obliquity signal found in Pleistocene age EEP records as evidence that changes in high latitude glaciation had an impact on productivity and SSTs. They suggested that an intensification in wind-driven upwelling and a shoaling of the thermocline promoted higher productivity.

These same factors most likely were responsible for the increase in productivity seen at the MMT and during CM6. The timing of nannofossil assemblage changes corresponds to the benthic  $\delta^{18}$ O record, which at this time record changes in Antarctic ice sheet volume. In particular, the sharp increase in the < 3 µm *Dictyococcites* specimens at CM6 suggests a causal link. EEP upwelling intensity was associated with high latitude cooling and ice growth. EAIS expansion intensified wind patterns by increasing latitudinal thermal gradients (e.g. Vincent and Berger, 1985) and caused increased upwelling and a greater supply of nutrients.

The occurrence of organic-rich rocks of the Monterey Formation and equivalent formations around the Pacific, which correspond to CM6 (Flower and Kennett, 1993), is the basis of the hypothesis. Here, we find conclusive evidence from the fossil record that there was enhanced marine production in the open ocean during CM6, supporting the Monterey hypothesis of Vincent and Berger (1985). This study does not refute the idea that the Monterey excursion was caused by continental carbon sequestration (Diester-Haass et al., 2009), but it does support at least a partial marine influence on the carbon isotope excursion.

#### CONCLUSIONS

The middle Miocene transition (MMT) marks a major expansion in ice sheets on East Antarctica and a stepping point in Cenozoic climate. Our results show that nannofossil productivity increased at the MMT and strengthened during peak Mi-3 glaciation and carbon isotope maxima 6 (CM6). The timing of nannofossil assemblage changes corresponds closely to these events as shown in the benthic isotope record. Diatoms are conspicuously absent from the glaciation interval and opal content peaks prior to the MMT. Diatoms were likely unable to inhabit the EEP during this time because of silica limitation. The opal peak seen could be the result of a brief change in deep-water circulation. Based upon the collected data, we propose that the Mi-3 glaciation intensified wind patterns, which resulted in enhanced EEP upwelling. Here we see a connection between high latitude forces and changes in oceanic primary productivity, creating a positive feedback for middle Miocene cooling.

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**Figure 3.1.** Early to middle Miocene events. MCO = Miocene climatic optimum, MMT = middle Miocene transition, CM6= carbon isotope maximum 6.



**Figure 3.2.** Present day location of Site U1338, modified from Expedition 320/321 Scientists (2010). The inset highlights the global location of the site map (square).



**Figure 3.3.** Geochemical, fossil, and grain size records from Site U1338. The geochemical results displayed are estimated CaCO<sub>3</sub>% (Lyle et al., in review), opal weight % (O. Romero, unpublished data), and benthic  $\delta^{18}$ O and  $\delta^{13}$ C measurements (A. Holbourn, unpublished data). The grain size record shows the frequency of sizes in a sample (warm colors indicate higher frequencies). Nannofossils are in the 2-20µm range and diatoms fall between 2-200µm. Also shown is the number of *Dictyococcites spp.* < 3µm specimens encountered in each slide. Highlighted are the opal peak, based upon the opal weight % (red bar); the middle Miocene transition (MMT), based upon the benthic  $\delta^{18}$ O record (blue bar); and carbon maxima 6 (CM6), the timing of which is based upon the  $\delta^{13}$ C record (grey bar).



**Figure 3.4.** Richness, evenness, and Shannon diversity values for samples from U1338. The shaded color bars represent distinct time intervals (see Figure 3.3 caption).



**Figure 3.5.** Percent abundances of nannofossil species and genera, not including specimens  $< 3\mu$ m in size. The last occurrence (LO) of *Sphenolithus heteromorphus* at 13.53 Ma is denoted by a star. This datum marks the top of nannofossil zone NN5. The color bands represent time intervals discussed in Figure 3.3.

Figure 3.5a



Figure 3.5b



**Figure 3.6.** Cluster analysis of nannoplankton species and genera from Site U1338. The clusters are divided by abundance and ecology.



**Figure 3.7** DCA plot of nannofossil samples. The samples are color-coded by time. The vector represents the envfit correlation between the ordination and opal wt. %.



**Figure 3.8** DCA plot of nannofossil species. The stars represent species and the circles are the samples seen in Figure 3.7.



**Figure 3.9.** During the interval of peak opal deposition, opal % varies inversely with the smaller fluctuations in the  $\delta^{18}$ O record and directly with those in the  $\delta^{13}$ C record. Grey bands illustrate increases in  $\delta^{18}$ O values. Some nannofossil taxa also show trends in relation to the  $\delta^{18}$ O curve. *Discoaster* and *Reticulofenestra* appear to peak at  $\delta^{18}$ O minima and *Helicosphaera* and *Sphenolithus* peak at maxima.



# **PLATE 3.1**

1. Coccolithus pelagicus	U1338B-36-2, 5-6cm	10µm
2. Coccolithus miopelagicus	U1338B-36-2, 5-6cm	21µm
3. Coronocyclus nitescens	U1338B-36-2, 5-6cm	13µm
4. Coronocyclus nitescens elliptical form	U1338C-38-1, 125-127cm	7µm
5. Cyclicargolithus floridanus	U1338C-39-6, 55-57cm	10µm
6. Calcidiscus leptoporous	U1338C-38-1, 125-127cm	5µm
7. Calcidiscus premacintyrei	U1338B-36-2, 5-6cm	7µm
8. Calcidiscus macintyrei	U1338B-36-2, 5-6cm	15µm
9. Pyrocyclus spp.	U1338B-36-3, 115-116cm	4µm
10. Umbilicosphaera rotula	U1338B-36-2, 5-6cm	6µm
11. Pontosphaera multipora?	U1338B-36-3, 155-116cm	11µm
12. Helicosphaera carteri?	U1338B-36-3, 115-116cm	16µm
13. Helicosphaera granulata	U1338C-38-4, 105-106cm	20µm
14. Helicosphaera burkei	U1338B-36-3, 115-116cm	15µm

# Plate 3.1



Coccolithus pelagicus



Coccolithus miopelagicus



Coronocyclus nitescens



Coronocyclus nitescens, elliptical form



 $Cyclicargolithus\ floridanus$ 



Calcidiscus leptoporous



Calcidiscus premacintyrei



Calcidiscus macintyrei



Pyrocyclus spp.



Umbilicosphaera rotula



Pontosphaera multipora



Helicosphaera carteri



Helicosphaera granulata



Helicosphaera burkei

# **PLATE 3.2**

1. Discoaster variabilis	U1338C-38-4, 105-106cm	15µm
2. Discoaster deflandrei	U1338B-38-4, 127-128cm	12µm
3. <i>Sphenolithus</i> spp. < 3µm	U1338B-36-2, 5-6cm	2µm
4. Sphenolithus compactus	U1338C-38-1, 125-127cm	4µm
5. Sphenolithus moriformis	U1338C-38-4, 135-137cm	5µm
6. Sphenolithus abies	U1338B-37-2, 115-117cm	7µm
7. Sphenolithus heteromorphus	U1338C-38-1, 125-127cm	13µm
8. <i>Dictyococcites</i> spp. < 3µm	U1338C-38-4, 135-137cm	2µm
9. Dictyococcites antarcticus 3-5µm	U1338B-36-2, 5-6cm	4µm
10. <i>Dictyococcites antarcticus</i> > 5µm	U1338C-38-1, 125-127cm	7µm
11. Reticulofenestra minuta	U1338B-38-4, 127-128cm	2µm
12. Reticulofenestra haqii	U1338C-38-1, 125-127cm	4µm
13. Reticulofenestra pseudoumbilicus 5-7μm	U1338C-39-6, 55-57cm	6µm
14. Reticulofenestra pseudoumbilicus >7μm	U1338B-36-2, 5-6cm	11µm
15. Reticulofenestra pseudoumbilicus round form	U1338C-39-3, 95-97cm 6µm	

# Plate 3.2



Discoaster variabilis



Discoaster deflandrei



*Sphenolithus* spp. > 3 micron



Sphenolithus compactus



Sphenolithus moriformis



Sphenolithus abies



Sphenolithus heteromorphus



Dictyococcites spp. > 3 micron



Dictyococcites antarcticus 3-5 micron



Dictyococcites antarcticus > 5 micron



Reticulofenestra minuta



Reticulofenestra haqii



Reticulofenetra pseudoumbilicusReticulofenestra pseudumbilicus5-7 micron> 7 micron



15 *R. pseudoumbilicus* round form

# **CONCLUSIONS**

The fossil record is a useful tool when it comes to understanding how climate and environment can affect organisms. In this dissertation I used nannofossils to better understand how nannoplankton communities responded to climate change over multiple time intervals. The results show that, in each instance, nannoplankton assemblage changes occurred in response to climatic forcing. In addition, these climatic effects had a long-term impact on the nannoplankton assemblages.

In each study immediate effects of climate on the nannoplankton assemblage were seen, the timing of which were proportional to the duration of climate change. In Chapter 1, early Eocene warming into and during the early Eocene climatic optimum (EECO) may have led to oceanic destratification, which facilitated *Reticulofenestra* expansion in the high latitudes. *Toweius* did not fair well during this time as is seen in its large abundance decrease. Despite the global cooling after the EECO and a return to conditions like those of the earlier Eocene, the global assemblage did not revert back to prior conditions nor was *Toweius* able to recover. Rather, global cooling following the EECO allowed *Reticulofenestra* to migrate to lower latitudes. *Reticulofenestra* came to dominate the global assemblage in the middle Eocene. The expansion and migration of this genus occurred over millions of years, the same scale as the duration of climate change. Interestingly, outside of the migration and expansion of *Reticulofenestra* and the demise of *Toweius*, the remainder of the assemblage was affected little. The assemblage was resilient to cooling into the Eocene-Oligocene boundary. During the Eocene, long-term climate change appears to have influenced only certain taxa, perhaps illustrating nannoplankton's ability to adapt.

The nannoplankton assemblages shifted abruptly in response to transient warming at the Paleocene-Eocene Thermal Maximum (PETM). Rapid warming caused surface temperatures to warm, the ocean to become more stratified, and increased run-off along coastal margins. Our results from Chapter 2 support interpretations of previous studies. Using quantitative statistical methods, we find that the open ocean assemblages responded to both increased temperature and decreased nutrients and the shelf-hemipelagic assemblages show an increase in nutrients and temperature and a decrease in salinity causing a decrease in primary production in the open ocean and an increase in primary production in the shelf-hemipelagic sites of this study. It

appears that the environmental changes associated with the onset of the PETM caused the high latitude taxa to adapt to warmer temperatures and less nutrient input. These adaptations carry on past the PETM. In addition, we are able to better define paleoecologies of nannoplankton taxa through the use of statistics coupled with environmental proxies. These findings can be applied to other intervals in the Paleogene.

Middle Miocene cooling did not result in an abrupt nannoplankton assemblage shift like that at the PETM. Rather, a more gradual response is seen in Chapter 3, which may be owed to the fact that this cooling event occurred ~4 times slower than warming at the PETM. At the middle Miocene transition (MMT) and the following carbon isotope maximum 6 (CM6), the nannoplankton assemblage indicates increased production in eastern equatorial Pacific (EEP) upwelling. It is characterized by an increase in *Dictyococcites* and *Sphenolithus abies* and a decline in warmer water taxa. Equatorial upwelling would have been impacted through glaciation by increased wind patterns stemming from an increased latitudinal temperature gradient. This event resulted in a long-term change in the assemblage.

The long-term impact of climate change on the community varies depending on the rate of change. In the slow rate of change study (Chapter 1), there are few changes in the biogeographic range of taxa in response to the Eocene warming and subsequent cooling. Rather, it is primarily *Reticulofenestra* that was impacted by environmental variation along with the demise of *Toweius*. The long-term impact of Eocene climate was the expansion and dominance of *Reticulofenestra* that lasted well into the Neogene Period. The continual abundances through the Eocene cooling in particular suggest the ability for nannoplankton to readily adapt to climate on long time scales.

The periods of faster temperature change, the PETM and MMT, showed a distinctive nannoplankton response. At the PETM, there were notable biogeographic shifts in both warm water and cool water taxa. Warmer water taxa spread into high latitude regions, but the cooler water nannoplankton increase in abundance in the lower latitudes of the open ocean. The changes in the nannoplankton community during the excursion extend through the remainder of the PETM and after the event. Cooler water taxa appeared to have adapted to warmer water conditions during the PETM and retained this ecological preference even after global temperatures returned to pre-excursion values. Similarly, the increase in *Dictyococcites* and *S. abies* during the MMT in the EEP persisted through the event and after. In the post-glacial

interval, warmer water taxa returned to the EEP, but *Dictyococcites* and *S. abies* do not change in abundance. These species appear to have occupied a space vacated by *Reticulofenestra*.

There are commonalities and trends between each of these studies that provide conclusions on how climate change effects nannoplankton populations. First, we find that the amount of time it takes for these observed assemblage changes to take place is proportional to the duration of the climate change and the rate of change. This simply means that the faster climate perturbation occurs, the faster the assemblage will change, which seems rather intuitive. The rate or duration does not imply a greater or lesser change in the assemblage. For example, the assemblage change found at the MMT in the EEP is greater than the assemblage response at Demerara Rise during the PETM. The variation in the nannoplankton assemblage response is impacted by regional distributions, as is observed at the PETM.

For all of the observed time intervals the nannoplankton assemblages were altered during the climate change interval and also on a long-term scale. At the PETM there was an abrupt assemblage response that resulted in an alteration of the nannoplankton community that persisted into the Eocene. The MMT and Mi-3 glaciation allowed *Dictyococcites* and *S. abies* to become very abundant in the EEP. *Dictyococcites* remained dominant in the EEP through the Miocene. The difference between the short and long term effects of climate are not as clear-cut during the Eocene. Climate facilitated the emergence of *Reticulofenestra*, which retained its global significance into the Neogene.

Finally, the studies show an individualistic response of taxa to climate change, rather than a wholesale assemblage alteration. The high latitude taxa modified their ecology and biogeographic range during the PETM while the low latitude taxa show little change. The warmer water taxa also appear to be unaffected by the MMT and Mi-3 glaciation as they return into the EEP after the event. Rather, it is the higher-productivity, cooler-water taxa that remain even after the glaciation. It is *Reticulofenestra* and *Toweius* that are most affected by Eocene climate, whereas the other major genera have surprisingly constant abundances throughout the interval.

These findings have implications for how communities change over long time scales and what drives the community composition. Here we find that on shorter time scales, it is environment that controls the nannoplankton assemblage composition. However, on longer time scales (10's of thousands of years and greater) the assemblage is not only the result of environment, but also climatic events that shaped the assemblage composition. Our results indicate that global warming and cooling not only cause biogeographic shifts, but also a fundamental change in the assemblage structure that follows the end of climate change. The assemblage observed at any given time is a product of forces that occurred in the geologic past and the local environment.

From these results we can project how nannoplankton communities will be affected by future global warming. With high rates of temperature change, biogeographic range shifts occur. It can be expected that nannoplankton taxa will migrate to higher latitudes over the coming decades. From this dissertation it is clear that climate change has a long-term impact on nannoplankton assemblages and, in a sense, the nannoplankton assemblage shifts are not reversible. Taxa adapt to climate change in an individualist way do not revert to prior ecological adaptations. It is unlikely that with the termination or mitigation of climate warming the nannoplankton community will return to one similar to preindustrial times.

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# APPENDIX A: SUPPLEMENTAL INFORMATION FOR CHAPTER 1

**Figure A.1.** Reproducing genera counts for Sample 1263b 5-3, 15-16cm. Two counts of 300 specimens, one count of 500 specimens, and once count of 300 on a regular smear slide are compared.



**Figure A.2.** The surface, thermocline, and benthic oxygen and carbon isotope record for Maud Rise (Sites 689 and 690), Kerguelen Plateau (Site 738), and Shatsky Rise (Site 1209).



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### Table A.1 Samples used for nannofossil assemblage counts

Sample List (Leg, Hole, Core, Section, Interval (cm))

Sample	Depth (mbsf)	Age model (Ma)
549 2-3, 20-21	201.7	36.97
549 3-1, 20-21	208.2	37.58
549 4-2, 20-21	219.2	39.07
549 5-4, 20-21	231.7	40.75
549 6-3, 20-21	239.7	41.83
549 7-2, 20-21	247.7	43.11
549 8-3, 20-21	258.7	44.97
549 9-1, 20-21	265.2	45.74
549 9-3, 20-21	268.2	46.11
549 10-1, 20-21	274.7	47.97
549 10-3, 20-21	277.7	48.82
549 10-5, 20-21	280.7	49.68
549 11-1, 20-21	284.2	50.68
549 11-2, 20-21	285.7	50.72
549 11-4, 20-21	288.7	50.78
549 11-5, 20-21	290.2	50.8
549 11-6, 20-21	291.7	50.83
549 11-7, 20-21	293.2	50.85
549 12-2, 20-21	295.2	50.89
549 13-5, 20-21	309.2	51.26
549 14-4, 20-21	317.2	52.04
549 15-3, 11-12	325.11	52.83
549 16-4, 20-21	336.2	53.92
549A 21-1, 19, 20	129.19	34.21
549A 25-2, 15-16	136.65	34.63
549A 28-2, 30-31	141.8	34.89
549A 33-2, 22.5-23.5	152.225	35.42
549A 38-1, 20-21	175.7	36.6
549A 42-1, 20-21	195.7	36.88
689B 14H-2, 20-21	121.90	34.55
689B 14H-6 20-21	127.90	35 35
689B 15H-6 22-23	137.60	36.82
689B 16H-5 20-21	145 60	37.89
689B 17H-2 20-21	150.80	40.86
689B 17H-5 21-22	155 31	43.66
690B 12H-2 20-21	100.85	37 17
690B 12H 2, 20 21	105.35	40.48
600B 13H-2 55-56	110 55	40.40 /5 0
690B 13H-5 20-21	110.35	47.02
690B 14H-2 20-21	120.20	47.02
600B 14H-5 20-21	120.20	40.51
6000 1 = 12, 20 = 21	120.75	43.02
600B 15H-2 122 124	120.02	50.07 E0.02
6000 15H-2, 133-134	120.14	50.82
600 15H 2 02 04	120.14	51.02
0300 IJII-Z, 33-34	10.00	J1.22

690B 15H-3, 135-136	132.45	51.39
690B 15H-3, 15-16	131.25	51.59
690B 15H-3, 55-56	131.65	51.79
690B 15H-3, 95-96	132.05	52.00
690B 15H-4, 10-11	132.70	52.12
690B 15H-4, 23-24	132.83	52.19
690B 15H-4, 37-38	132.97	52.26
690B 15H-4, 50-51	133.10	52.33
690B 15H-4, 60-61	133.20	52.38
690B 15H-4, 70-71	133.30	52.43
690B 15H-4, 80-81	133.40	52.48
690B 15H-4, 90-91	133.50	52.53
690B 15H-4, 104-105	133.64	52.60
690B 15H-4, 117-118	133.77	52.67
690B 15H-4, 130-131	133.90	52.73
690B 15H-5, 21-22	134.31	52.94
690B 15H-5, 54-55	134.64	53.10
690B 15H-6, 21-22	135.81	53.70
690B 16H-2, 21-22	139.51	53.88
690B 16H-5, 22-23	144.02	53.99
690B 17H-3, 20-21	150.70	54.18
690B 17H-5, 22-23	153.72	54.3
762C 4X-1, 40-41	189.4	34.1
762C 5X-1, 41-42	198.91	34.73
762C 6X-1, 40-42	208.4	35.49
762C 7X-1, 40-41	217.9	36.26
762C 8X-1, 41-42	227.41	36.71
762C 9X-1, 21-22	236.71	36.91
762C 10X-1, 40-41	246.4	37.15
762C 11X-1, 40-41	255.9	38.36
762C 12X-2, 40-41	266.9	39.75
762C 13X-1, 40-41	274.9	40.91
762C 14X-1, 40-41	284.4	42.56
762C 15X-1, 40-41	293.9	43.99
762C 16X-1, 39-40	303.39	45.43
762C 17X-1, 40-42	312.9	46.81
762C 18X-1, 40-41	322.4	47.06
762C 18X-2, 40-41	323.9	47.09
762C 18X-3, 40-41	325.4	47.13
762C 18X-4, 40-41	326.9	47.17
762C 18X-5, 40-41	328.4	47.81
762C 18X-6, 40-41	329.9	49.57
762C 19X-1, 49-50	331.99	49.94
762C 19X-2, 49-50	333.49	50.21
762C 19X-3, 49-50	334.99	50.47
762C 19X-4, 0-1	335.99	50.65
762C 19X-4, 49-50	336.49	50.72
762C 19X-5, 49-50	337.99	50.82
762C 20X-1, 40-41	341.4	51.07
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762C 21X-1, 40-41	350.9	51.76
762C 21X-1, 100-101	351.5	51.8
762C 22X-1, 40-42	360.4	52.44
762C 23X-1, 40-41	369.9	53.11
762C 24X-1, 39-40	379.39	53.27
762C 25X-1, 40-41	388.9	53.43
762C 26X-2, 40-41	399.9	53.93
762C 27X-1, 40-41	402.9	54
762C 28X-1, 40-41	412.4	54.23
1135A 3R-2, 20-21	20.1	40.78
1135A 4R-2, 20-21	29.5	41.14
1135A 5R-2, 20-21	39	41.51
1135A 6R-2, 20-21	48.5	41.88
1135A 7R-2, 20-21	57.8	42.24
1135A 8R-2, 20-21	66.8	42.59
1135A 10R-2, 20-21	85.9	43.32
1135A 11R-2, 20-21	95.6	43.7
1135A 12R-2, 20-21	105.1	46.04
1135A 13R-1, 20-21	113.2	46.54
1135A 15R-2, 20-21	133.9	47.65
1135A 16R-3, 20-21	142.1	48.1
1135A 16R-3, 20-21	145.1	48.26
1135A 17R-2, 20-21	153.3	48.7
1135A 17R-5, 20-21	157.8	48.95
1135A 19R-1, 20-21	171	49.66
1135A 19R-3, 20-21	174	49.82
1135A 20R-2, 20-21	182.1	50.26
1135A 20R-5, 20-21	186.6	50.5
1135A 21R-2, 20-21	191.7	50.84
1135A 21R-5, 50-51	196.5	51.31
1135A 22R-1, 20-21	199.8	51.64
1135A 23R-1, 22-23	209.42	52.58
1135A 23R-1, 60-61	210	52.64
1135A 23R-2, 20-21	211.1	52.75
1135A 23R-2, 100-101	211.9	52.83
1135A 25R-1, 20-21	228.7	54.47
1137A 21R-1, 20-21	190.1	35.27
1137A 21R-CC, 6.5-7.5	199	36.60
1210B 13H-7, 21-22	122.91	34.09
1210B 14H-1, 33-34	123.33	34.18
1210B 14H-2, 82-83	125.33	34.97
1210B 14H-4, 120-121	128.45	37.09
1210B 14H-5, 120-121	130.34	38.38
1210B 14H-6, 45-46	131	38.83
1210B 15H-2, 20-21	134.4	41.14
1210B 15H-5, 45-46	139.14	44.37
1210B 16H-2, 0-1	143.73	45.28
1210B 16H-4, 0-1	147.05	46.11
1210B 16H-5, 50-51	148.55	46.36

1210B 16H-6, 50-51	150.05	46.62
1210B 16H-6, 100-101	150.55	46.71
1210B 17H-1, 100-101	152.74	47.32
1210B 17H-2, 100-101	154.24	47.79
1210B 17H-3, 0-1	154.74	47.94
1210B 17H-3, 50-51	155.24	48.10
1210B 17H-3, 100-101	155.74	48.26
1210B 17H-5, 50-51	158.23	49.04
1210B 17H-6, 50-51	159.73	49.51
1210B 18H-3, 50-51	164.82	50.97
1210B 18H-5, 50-51	167.7	51.57
1210B 18H-6, 50-51	169.2	51.87
1210B 19H-1, 50-51	171.2	52.29
1210B 19H-2, 100-101	173.2	52.70
1210B 19H-4, 0-1	175.2	53.11
1210B 19H-5, 50-51	177.26	53.54
1210B 20H-1, 50-51	180.52	54.21
1263A 22H-2, 20-21	194	49.35
1263A 22H-5, 20-21	198.5	49.64
1263A 22H-7, 18-19	201.5	49.85
1263B 5H-3, 15-16	87.15	34.30
1263B 6H-5, 20-21	99.7	36.50
1263B 7H-3, 20-21	106.2	37.95
1263B 8H-3, 20-21	115.7	39.09
1263B 9H-3, 20-21	125.2	40.18
1263B 10H-5, 20-21	137.7	42.39
1263B 11H-5, 20-21	147.2	43.52
1263B 12H-5, 20-21	156.7	44.90
1263B 13H-5, 35-36	166.35	46.42
1263B 14H-3, 20-21	172.7	47.26
1263B 15H-3, 20-21	180.2	48.30
1263B 16H-1, 20-21	186.7	48.79
1263B 16H-5, 20-21	192.7	49.13
1263B 16H-7, 20-21	195.7	49.30
1263B 18H-2, 20-21	198.9	49.58
1263B 18H-3, 20-21	200.4	49.72
1263B 19H-2, 20-21	202.7	50.00
1263B 19H-3, 20-21	204.2	50.13
1263B 20H-2, 20-21	206.6	50.44
1263B 20H-4, 18-19	209.58	50.67
1263B 20H-7, 20-21	214.08	50.94
1263B 21H-2, 20-21	216.1	51.26
1263B 21H-4, 20-21	219.1	51.61
1263B 22H-3, 20-21	227.1	52.36
12638 23H-4, 20-21	238.1	53.17
1263B 24H-5, 20-21	249.1	53.39
1263B 25H-3, 20-21	255.6	53.53
1263B 26X-5, 20-21	268.1	53.81
1263B 2/X-4, 20-21	2/5.8	54.01

## **Table A.2.** Datums used to construct the age models and depths.

Site	Datum	Depth	Reference for datum	Datum Age (Ma)	Reference for age
Exmouth Plateau					
762C	LO Coccolithus	(mbst)	Siesser and	22.0	
	formosus	171	Bralower, 1992	32.9	Blaj et al., 2009
	barbadiensis FO Isthmolithus	200	Bralower, 1992 Siesser and	34.8	Blaj et al., 2009
	recurvus	222	Bralower, 1992	36.6	Backman, 1986
	grandis	246	Bralower, 1992	37.1	Backman, 1987
	base C18r	272	Galbrun, 1992	40.4	2004 GTS
	FO Reticulofenestra umbilicus FO Nannotetrina	284	Slesser and Bralower, 1992 Slesser and	42.5	Backman, 1987
	fulgens	312.5	Bralower, 1992	46.8	Agnini et al., 2006
	base C21n	328	Galbrun, 1992	47.2	2004 GTS
	FO Discoaster sublodoensis	329.5	Siesser and Bralower, 1992 Siesser and	49.5	Agnini et al., 2006
	orthostylus FO Discoaster	336.26	Bralower, 1992 Siesser and	50.7	Agnini et al., 2006
	lodoensis	369.5	Bralower, 1992 Siesser and	53.1	Agnini et al., 2007
	contortus	393	Bralower, 1992	53.5	Agnini et al., 2007
	base C24n.3n	394.58	Galbrun, 1992	53.8	2004 GTS
	diastypus	407	Bralower, 1992	54.1	Agnini et al., 2007
Goban Spur					
549/549A	Ι Ο Isthmolithus	(mbsf)			
	recurvus	103	Mueller, 1985	32.5	Villa et al., 2008
	LO Discoaster saipanensis FO Isthmolithus	132.1	Mueller, 1985	34.4	Blaj et al., 2009
	recurvus FO Chiasmolithus	175.5	Mueller, 1985	36.6	Backman 1986 Berggren et al.,
	oamaruensis	203.9	Mueller, 1985	37.0	1995
	base C20n	246.13	Townsend, 1985	42.7	2004 GTS
	LO Chiasmolithus gigas	251.09	Mueller, 1985	44.0	Backman, 1986
	FO Chiasmolithus gigas	268.16	Mueller, 1985	46.1	Agnini et al., 2006
	base C22n	284.27	Townsend, 1985	50.7	2004 GTS
	top C24n.3n EO <i>Di</i> scoaster	307.62	Townsend, 1985	51.1	2004 GTS
	diastypus	338.05	Mueller, 1985	54.1	Agnini et al., 2007
Kerguelen Plateau 738B/C		(mbsf)			
	FO Ismolithus recurvus	39.96	Wei and Thierstein, 1991	36.6	Backman 1986
	LO Chiasmolithus solitus	70.83	Wei and Thierstein, 1991	40.4	Berggren et al., 1995
	FO Reticulofenestra umbilicus	119.21	Wei and Thierstein, 1991 Wei and Thierstein	42.5	Backman, 1987
	fulgens	204.93	1991	46.8	Agnini et al., 2006
	⊢O Discoaster sublodoensis	227.03	Wei and Thierstein, 1991	49.5	Agnini et al., 2006
	FO Discoaster lodoensis	260.28	Wei and Thierstein, 1991	53.1	Agnini et al., 2007
	FO Discoaster diastypus	283.85	wei and Thierstein, 1991	54.1	Agnini et al., 2007
	FO Discoaster multiradiatus	295.5	Wei and Thierstein, 1991	56.0	Agnini et al., 2007

Kerguelen					
Plateau 1135A	FO Reticulofenestra	(mbsf)	Arney and Wise,	40 5	
	umbilicus	64.6	2003 Arney and Wise	42.5	Backman, 1987
	LO Chiasmolithus gigas	103.4	2003	44.0	Backman, 1986
	FO Chiasmolithus gigas	105.15	2003	46.1	Agnini et al., 2006
	LO Tribrachiatus orthostylus	190.25	Arney and Wise, 2003	50.7	Agnini et al., 2006
	LO Fasciculithus spp.	231	Arney and Wise, 2003	54.7	Agnini et al., 2007
Kerquelen					
Plateau 1137A		(mbsf)			
	LO Istnmolitnus recurvus Eocene/Oligocene	171	Arney and Wise, 2003	32.5	Villa et al., 2008
	Boundary LO	100.0	Shipboard Scientific	33.8	
	Hantkenina	180.3	Party, 2000 Arney and Wise,	36.6	Palike et al., 2006
	FO Ismolithus recurvus	199	2003	30.0	Backman 1986
Maud Rise 689B		(mbsf)			
	top C15n	124	Florindo and Roberts,2005	34.8	2004 GTS
	base C15n	124.9	Florindo and Roberts,2005	35.0	2004 GTS
	top C16n.1n	128.3	Florindo and Roberts,2005	35.4	2004 GTS
	base C16n.1n	134.2	Florindo and Roberts,2005	35.6	2004 GTS
	top C17n.1n	135.5	Florindo and Roberts,2005	36.7	2004 GTS
	base C17n.1n	144.4	Florindo and Roberts,2005	37.2	2004 GTS
	top C18n.1n	145.8	Florindo and Roberts,2005	38.0	2004 GTS
Maud Rise 690B		(mbsf)	Florindo and	07.0	
	base C17r.1r	99.3	Roberts,2005 Elorindo and	37.3	2004 GTS
	base C19n	105.5	Roberts,2005	40.6	2004 GTS
	top C21n	108.7	Roberts,2005	45.4	2004 GTS
	base C22n	123.5	Roberts,2005	49.4	2004 GTS
	orthostylus	129.9	Pospichal and Wise, 1990	50.7	Agnini et al., 2006
	top C24r	136	Ali et al., 2000	53.8	2004 GTS
	diastypus	148.8	1990	54.1	Agnini et al., 2007
	Paleocene/Eocene Boundary	170.64	Kennett and Stott, 1991	55.0	Cande and Kent, 1995
Shateky Pico					
1209		(mcd)			
	LO Discoaster saipanensis	139.445	Bralower, 2005	34.4	Blaj et al., 2009
	LO Chiasmolithus gigas	152.76	Bralower, 2005	44.0	Backman, 1986
	FO Chiasmolithus gigas	166.17	Bralower, 2005	46.1	Agnini et al., 2006
	orthostylus	187.93	Bralower, 2005	50.7	Agnini et al., 2006
	diastypus	210.58	Bralower, 2005	54.1	Agnini et al., 2007
Shatsky Rise					
1210B	LO Coccolithus	(mbsf)		00.0	
	formosus	116.7	Bralower, 2005	32.9	Blaj et al., 2009
	LO Discoaster	124.5	Bralower, 2005	34.4	Blaj et al., 2009

	saipanensis				
	FO Reticulofenestra umbilicus	137.1	Bralower, 2005	42.5	Backman, 1987
	LO Chiasmolithus gigas	138.6	Bralower, 2005	44.0	Backman, 1986
	FO Chiasmolithus gigas	147	Bralower, 2005	46.1	Agnini et al., 2006
	FO Nannotetrina fulgens	151.1	Bralower, 2005	46.8	Agnini et al., 2006
	orthostylus	163.5	Bralower, 2005	50.7	Agnini et al., 2006
	FO Discoaster diastypus	180	Bralower, 2005	54.1	Agnini et al., 2007
	Paleocene/Eocene Boundary	184.32	Colosimo et al., 2006	55.0	Cande and Kent, 1995
•		(mcd)			
	top C13n	83.62	Bowles, 2006	33.3	2004 GTS
	base C13n	89.42	Bowles, 2006	33.7	2004 GTS
	LO Discoaster saipanensis	104.1	Shipboard Scientific Party, 2004	34.4	Blaj et al., 2009
	FO Isthmolithus recurvus	116.58	Shipboard Scientific Party, 2004	36.6	Backman 1986
	FO Porticuloasphaera semiinvoluta	124	Shipboard Scientific Party, 2004	38.0	2004 GTS
	top C19n	147.8	Bowles, 2006	40.4	2004 GTS
	base C19n	149.2	Bowles, 2006	40.6	2004 GTS
	FO Reticulofenestra umbilicus	159.62	Shipboard Scientific Party, 2004	42.5	Backman, 1987
	LO Chiasmolithus gigas	174.08	Shipboard Scientific Party, 2004	44.0	Backman, 1986
	FO Chiasmolithus gigas	189.12	Shipboard Scientific Party, 2004	46.1	Agnini et al., 2006
	LO Discoaster Iodoensis	209.39	Shipboard Scientific Party, 2004	48.4	Agnini et al., 2006
	FO Discoaster sublodoensis	228.98	Shipboard Scientific Party, 2004	49.5	Agnini et al., 2006
	FO Discoaster Iodoensis	276.06	Shipboard Scientific Party, 2004	53.1	Agnini et al., 2007
	FO Discoaster diastypus	329.39	Shipboard Scientific Party, 2004	54.1	Agnini et al., 2007

#### Walvis Ridge 1263A/B

 $^{\ast}$  Depth is giving in either meters below sea floor (mbsf) or meters composite depth (mcd).

#### Plate A.1

#### Reticulofenestrids

- 1. *Reticulofenestra dictyoda* Sample 689B, 14-6, 20-21cm length: 5µm
- 2. *Reticulofenestra dictyoda* Sample 690B, 15-3, 55-56cm length: 7µm
- 3-4. *Reticulofenestra daviesii* Sample 549A, 21-1, 19-20cm length: 5μm
- 5. *Reticulofenestra wadeae* Sample 762C, 6-1, 40-41cm length: 6µm
- 6. *Reticulofenestra reticulata (Cribrocentrum)* Sample 689B, 15-6, 22-23cm length: 7μm
- 7. *Reticulofenestra umbilica* Sample 549A, 21-1, 19-20cm length: 17µm
- 8. Dictyococcities bisecta (Reticulofenestra) Sample 689B, 15-6, 22-23cm length: 10μm
- 9. *Reticulofenestra samodurovii* Sample 549A, 28-2, 30-31cm length: 10μm















# **APPENDIX B: SITE U1338 NANNOFOSSIL COUNTS**

#### Table B.1 Site U1338 nannofossil counts

	6	Garting	Tabasal	CCSF-A	A	tching	vergrowth	alcidiscus leptoporous	alcidiscus macintyrei	alcidiscus premacintyrei	occolithus miopelagicus	occolithus pelagicus	oronocyclus nitescens	oronocyclus nitescens elliptical	yclicargolithus floridanus
ноге	Core	Section	Interval	(m)	Age	ш	0	0	0	0	0	0	0	0	0
U1338C	36	4	15-17	354.52	13.253	E2		3	0	0	32	50	0	0	2
U1338C	30	4	35-37	354.72	13.260	E2		4	1	5	4	40	0	0	1
U1338C	30	4	55-57 105 106	354.92	13.267	E2		2	2	1	- 11	42	0	0	0
U1330D	30	1	115 116	354.99	13.209	E2	01	4	4	0	5	00 E1	0	0	0
U1330D	26	1	125 126	355.09	12 280	E2	01	2	1	2	9	25	0	2	0
013300	30	1	133-130 E.C	355.29	12.200	L2 50		5	1 2	2	0	20	1	0	0
U1330D	26	2	5-0 25-26	255.49	12.20/	E2		5	0	2	6	50	1	0	4
U1338B	36	2	2J-20 45-46	355.80	13 301	E2		2	0	2	1	52 24	0	0	0
U1338B	36	2	4J-40 65-66	356.09	13 308	E2		9	1	1	5	24	1	0	1
U1338B	36	2	85-86	356.29	13 315	F1		4	0	0	16	35	0	0	7
U1338B	36	2	105-106	356.49	13.322	F1		5	0	0	9	23	0	0	, 1
U1338B	36	- 2	125-126	356.69	13.329	F1		4	2	1	4	36	0	0	0
U1338B	36	2	145-146	356.89	13.336	E1		3	0	2	2	28	0	0	3
U1338B	36	3	15-16	357.09	13.343	E1		7	4	1	11	32	0	0	1
U1338B	36	3	35-36	357.29	13.350	E2		9	3	0	4	45	0	0	2
U1338B	36	3	55-56	357.49	13.356	E2		5	1	4	5	54	1	0	1
U1338B	36	3	75-76	357.69	13.363	E2		2	0	1	12	55	0	0	3
U1338B	36	3	95-96	357.89	13.370	E1		5	2	2	13	52	0	0	7
U1338B	36	3	115-116	358.09	13.377	E2		6	0	1	5	60	1	0	1
U1338B	36	3	135-136	358.29	13.384	E2		7	3	2	11	37	0	0	1
U1338B	36	4	15-16	358.59	13.395	E2		1	0	1	16	24	1	0	0
U1338B	36	4	35-36	358.79	13.402	E2		3	1	0	5	28	0	0	3
U1338B	36	4	55-56	358.99	13.409	E2		1	1	0	1	25	0	0	0
U1338B	36	4	85-86	359.29	13.419	E2		7	1	3	1	21	1	0	1
U1338B	36	4	105-106	359.49	13.426	E2		1	0	3	11	34	0	0	1
U1338B	36	4	125-126	359.69	13.433	E2		12	1	1	3	22	0	0	0
U1338B	36	4	145-146	359.89	13.440	E2		8	0	2	0	15	0	0	0
U1338B	36	5	15-16	360.09	13.447	E2	01	7	2	2	3	49	0	0	1
U1338B	36	5	45-46	360.39	13.458	E2		0	1	3	0	44	0	0	1
U1338B	36	5	65-66	360.59	13.464	E2		6	1	1	3	25	0	0	0
U1338B	36	5	86-87	360.8	13.472	E2		3	1	2	2	33	0	0	0
U1338B	36	5	115-116	361.09	13.482	E2		7	0	0	4	15	1	1	0
U1338B	36	5	135-136	361.29	13.489	E1		4	0	1	0	15	0	1	0
U1338B	36	6	5-6	361.5	13.496	E2		9	0	1	1	13	0	1	0
U1338B	36	6	25-26	361.69	13.503	E1		10	0	6	1	14	0	0	0
U1338C	37	1	90-92	361.87	13.509	E1		5	2	2	1	37	0	0	3
U1338C	37	1	110-112	362.07	13.516	E2		5	1	1	0	22	0	0	1
U1338C	37	1	130-132	362.27	13.523	E2		10	0	2	0	21	0	1	1
U1338C	37	1	140-142	362.37	13.527	E2		2	0	3	4	33	0	0	3

CCSF-A (m)	Dictyococcities <3 microns	Dictyococcities 3-5 microns	Dictyococcities antarcticus	Discoaster deflandrei	Discoaster exilis	Discoaster pansus	Discoaster spp.	Discoaster variabilis	Hayaster perplexus	Helicosphaera burkei	Helicosphaera carteri	Helicosphaera granulata	Heliocsphaera minuta	Helicosphaera scissora	Orthorhabdus serratus
354.52	53	362	36	0	1	0	1	1	0	0	0	7	0	0	0
354.72	70	141	108	0	0	0	3	0	0	0	0	2	0	0	0
354.92	85	125	145	0	0	0	4	0	0	0	0	3	0	0	0
354.99	31	102	93	0	0	0	9	0	0	0	0	4	0	0	0
355.09	53	212	113	0	0	0	4	0	0	1	0	2	0	0	0
355.29	52	158	104	0	0	0	0	0	0	0	0	0	0	0	0
355.49	25	53	122	0	0	1	5	2	0	0	0	2	0	0	0
355.69	32	123	175	0	0	0	3	1	0	1	0	0	0	0	0
355.89	22	118	168	0	0	0	0	0	0	0	0	2	0	0	0
356.09	45	104	180	0	0	0	3	0	0	3	0	1	0	0	0
356.29	11	153	131	0	0	0	1	3	0	3	0	5	0	0	0
356.49	32	226	150	0	0	0	0	0	0	5	0	2	0	0	0
356.69	17	172	152	0	0	0	3	0	0	7	0	12	0	0	0
356.89	29	167	150	0	0	0	1	1	0	6	0	1	0	0	0
357.09	28	112	158	0	1	0	4	4	0	6	0	5	0	0	0
357.29	40	140	126	1	0	0	3	0	0	4	0	2	0	0	0
357.49	45	104	99	0	0	0	9	1	0	6	0	6	3	0	0
357.69	271	156	105	0	0	0	8	5	0	6	0	4	0	0	0
357.89	281	106	102	0	0	0	3	2	0	10	1	9	0	0	0
358.09	81	130	115	0	0	0	3	0	0	10	0	8	0	0	0
358.29	41	107	156	0	0	0	3	1	0	3	0	5	0	0	0
358.59	20	128	149	0	0	0	3	0	0	3	0	6	0	0	0
358.79	41	121	145	0	0	2	2	1	0	2	0	4	0	0	0
358.99	16	103	172	0	0	0	5	0	0	4	0	1	0	0	0
359.29	26	80	157	0	0	0	1	3	0	1	0	2	0	0	0
359.49	0	33	100	0	0	0	2	1	0	1	0	2	0	0	0
320 80	202	140	125	0	0	0	1	1	0	5	0	2	0	0	0
360.09	202	136	82	0	1	0	0	1	0	3	0	8	0	0	0
360.39	159	110	131	0	0	0	0		0	4	0	3	0	0	0
360.59	149	71	144	0	0	0	0	0	0	8	0	7	0	0	0
360.8	73	46	171	0	0	0	0	0	0	9	0	4	0	0	0
361.09	197	50	114	0	0	0	0	2	0	2	0	5	0	0	0
361.29	439	93	104	1	0	0	2	0	0	10	0	4	0	0	0
361.5	273	142	166	0	0	0	1	0	0	2	0	0	0	0	0
361.69	698	129	109	0	0	0	0	0	0	7	0	2	0	0	0
361.87	144	125	62	0	0	0	2	1	0	4	0	13	1	0	0
362.07	23	83	114	0	0	0	4	0	0	0	0	2	0	0	0
362.27	710	175	91	0	0	0	0	0	0	2	0	1	0	0	0
362.37	186	113	156	0	1	0	1	0	0	14	0	0	0	0	0

CCSF-A (m)	Pontosphaera discopora	Pyrocyclus spp.	Reticulofenestra haqii	Reticulofenestra minuta	Reticulofenestra pseudoumbilicus	Reticulofenestra pseudoumbilicus lg	Reticulofenestra pseudoumbilicus w/plug	Reticulofenestra round sp.	Sphenolithus <3 microns	Sphenolithus abies form	Sphenolithus compactus	Sphenolithus heteromorphus	Sphenolithus moriformis	Sphenolithus moriformis large
354.52	0	0	85	20	25	28	7	0	13	9	8	0	5	0
354.72	0	0	24	4	12	54	0	0	1	13	3	0	2	0
354.92	0	1	25	6	10	39	0	0	6	20	0	0	3	0
354.99	0	0	43	5	7	36	0	0	4	6	2	0	1	0
355.09	0	0	41	29	20	32	0	0	8	28	3	0	2	0
355.29	0	1	72	14	13	27	0	0	5	51	8	0	1	0
355.49	0	0	35	8	4	22	0	0	1	21	3	0	3	0
355.69	0	0	35	6	13	15	0	0	7	18	7	0	1	0
355.89	0	0	35	3	10	19	0	0	5	34	4	0	0	0
356.09	0	0	27	10	7	10	0	0	4	28	5	0	0	0
356.29	0	0	32	8	/	16	0	0	6	34	1	0	1	0
356.49	0	1	20	10	10	10	0	0	4	19	4	0	1	0
350.09	0	1	22	10	4	25	0	0	4	32 32	14	0	U E	0
350.09	0	0	17	4	14	14	0	0	3	20	14	0	5	0
357.09	0	0	24	4	14	20	0	0	4 5	27	5	0	ц С	0
357 49	1	0	14	-	17	20	0	0	3	27	5	0	10	0
357.69	1	0	25	6	16	46	0	0	5	23	4	0	5	0
357.89	0	2	33	6	6	24	0	0	5	11	3	0	8	0
358.09	1	2	34	5	5	26	0	0	1	42	2	0	1	0
358.29	0	0	19	12	14	22	0	1	1	30	1	0	0	0
358.59	0	0	29	20	14	37	0	0	3	17	0	0	2	0
358.79	0	0	31	10	15	31	0	0	7	24	4	0	0	0
358.99	1	3	19	11	18	41	0	0	0	20	8	0	1	0
359.29	0	0	18	10	11	46	0	1	4	25	1	0	1	0
359.49	1	0	25	2	15	35	0	0	1	3	1	0	2	0
359.69	0	0	21	19	14	60	0	0	5	28	5	0	1	0
359.89	0	0	51	15	26	35	0	0	10	34	2	1	3	0
360.09	0	0	63	20	17	33	7	0	14	15	9	0	4	1
360.39	0	1	34	13	15	19	0	0	2	39	4	0	2	0
360.59	0	1	21	10	9	16	0	0	8	60	3	0	3	0
360.8	0	2	33	14	10	30	0	0	2	41	4	0	4	0
361.09	0	0	15	4	18	35	0	0	7	60	9	0	6	0
361.29	2	2	14	9	10	41	0	0	10	70	10	0	9	0
361.5	0	1	24	1	32	29	0	0	7	28	5	0	4	0
361.69	0	0	51	16	19	29	0	0	12	63	2	0	3	0
361.87	0	0	79	14	30	23	0	0	7	38	2	0	6	0
362.07	0	0	53	2	29	57	0	0	3	7	3	0	1	0
362.27	0	0	68	18	37	12	5	0	8	38	18	0	1	0
362.37	1	0	9	14	22	59	0	0	7	29	2	0	2	0

CCSF-A (m)	Triquetrorhabdulus millowii	Triquerorhabdulus rioii	Umbilicosphaera rotula
354.52	0	0	1
354.72	0	0	1
354.92	0	0	2
354.99	1	0	0
355.09	0	0	1
355.29	0	0	2
355.49	0	0	1
355.69	0	0	1
355.89	0	0	4
356.09	0	0	4
356.29	0	0	2
356.49	0	0	0
356.69	0	0	1
356.89	0	0	5
357.09	0	0	4
357.29	0	0	3
357.49	1	0	5
357.69	0	0	7
357.89	1	0	5
358.09	0	0	5
358.29	0	0	1
358.59	0	0	2
358.79	0	0	1
358.99	0	0	0
359.29	0	0	1
359.49	0	0	0
359.69	0	0	4
359.89	0	0	1
360.09	0	0	1
360.39	0	0	2
360.59	0	0	5
360.8	0	0	0
361.09	0	0	0
361.29	0	0	1
361.5	0	0	0
361.69	0	0	0
361.87	1	0	2
362.07	0	0	0
362.27	0	0	2
362.37	0	0	0

Hole	Core	Sect	Interval	CCSF-A	Age	tching	Overgrowth	calcidiscus leptoporous	alcidiscus macintyrei	alcidiscus premacintyrei	coccolithus miopelagicus	occolithus pelagicus	coronocyclus nitescens	coronocyclus nitescens elliptical	cyclicargolithus floridanus
	27	Ject.	10.12	262 57	13 533	ш = Э	0	2	0	0	4	40	0	2	1
U1336C	37 27	2	20.22	302.37	13.555	L2 50		2	0	1	-4	40	0	2	1
U1336C	37	2	50-52	362.77	13.540	E2		2	1	1	1	12	0	1	2
U1336C	37 27	2	50-52 70 72	262.97	12 554	E2		1	1	4	4	20 42	0	2	6
U1338C	37	2	00-02	363 37	13 561	E2		6	1	1	0	38	0	0	3
U1338C	37	2	120-122	363.67	13.501	E2		2	1	3	14	35	0	1	5
U1336C	27	2	140 142	262 07	12 570	L2 50		2	0	1	14	22	0	1	, E
U1338C	37	2	20-22	364 17	13 580	E2		1	0	0	2	12	0	0	0
U1336C	27	2	20-22	264.27	12 506	L2 50		4 2	1	0	1	12	2	0	0
U1338C	37	3	40-42 60-62	364.57	13.590	E2		2	1	1	3	24	0	0	2
U1338C	37	3	80-82	364.37	13 610	E2		1	0	1	5	15	0	0	2
U1338C	37	3	100-102	364.97	13 617	E2		7	1	1	4	15	0	0	0
U1338C	37	3	120-122	365 17	13 624	E2		2	0	0	1	23	0	0	1
U1338C	37	3	140-142	365 37	13 631	F1		1	0	3	3	15	0	0	4
U1338C	37	4	10-12	365 57	13 638	E2		4	1	1	1	15	0	0	1
U1338C	37	4	40-42	365.87	13 648	F1	01	-	0	2	4	20	0	0	1
U1338C	37	4	60-62	366.07	13 655	F2	01	6	1	0	0	20	0	1	1
U1338C	37	4	80-82	366.27	13 662	F2		1	0	0	4	30	0	0	2
U1338C	37	4	110-112	366 57	13 673	F1		2	1	0	1	30	0	0	1
U1338C	37	4	130-132	366 77	13 680	E1		2	0	1	0	20	0	0	0
U1338C	37	5	0-2	366.97	13 687	E2		5	0	0	7	12	0	0	4
U1338B	37	2	115-116	367.03	13 689	E2		1	0	1	, 1	28	0	1	-
U1338B	37	2	135-136	367.03	13 696	E2		2	0	3	3	38	0	0	1
U1338B	37	2	5-6	367.23	13 703	F2		8	1	1	2	29	0	0	3
U1338B	37	3	25-26	367.43	13 710	E2		4	0	0	2	27	0	0	2
U1338B	37	3	45-46	367.83	13 717	E2		т 4	0	3	7	6	0	0	5
U1338B	37	3	65-66	368.08	13 725	E2		1	0	3	4	27	1	0	3
U1338B	37	3	95-96	368 33	13 734	F2		1	0	0	3	14	0	0	2
U1338B	37	3	115-116	368 58	13 743	F2		4	0	2	2	12	0	0	2
U1338B	37	3	135-136	368.78	13,750	F2		0	0	2	5	24	1	0	2
U1338B	37	4	15-16	369.08	13,760	F2		1	0	-	1	14	0	0	0
U1338B	37	4	35-36	369.28	13,767	F2		3	0	4	- 8	20	1	0	4
U1338B	37	4	55-56	369.43	13,773	F2		5	1	3	4	22	1	1	3
U1338B	37	4	76-77	369.69	13.781	E2	01	0	0	1	6	12	0	0	8
U1338B	37	4	95-96	369.88	13.788	E2		0	0	2	6	25	1	0	10
U1338B	37	4	115-116	370.08	13.795	E2		4	1	0	1	20	0	0	5
U1338B	37	4	145-147	370.38	13.806	E2		1	- 1	1	- 2	33	0	0	-
U1338B	37	5	17-18	370.55	13.812	E2		1	0	1	10	18	0	0	1
U1338B	37	5	37-38	370.8	13.820	E2		0	0	1	7	29	0	0	1
U1338B	37	5	57-58	371	13.827	E2		2	1	1	8	34	0	0	9

CCSF-A (m)	Dictyococcities <3 microns	Dictyococcities 3-5 microns	Dictyococcities antarcticus	Discoaster deflandrei	Discoaster exilis	Discoaster pansus	Discoaster spp.	Discoaster variabilis	Hayaster perplexus	Helicosphaera burkei	Helicosphaera carteri	Helicosphaera granulata	Heliocsphaera minuta	Helicosphaera scissora	Orthorhabdus serratus
362.57	131	60	141	0	0	0	6	1	0	0	0	0	0	0	0
362.77	574	194	167	0	0	0	0	0	0	0	0	1	0	0	0
362.97	617	153	96	0	0	0	0	2	0	5	0	5	0	0	0
363.17	238	103	133	0	0	0	2	0	0	0	0	4	0	0	0
363.37	279	83	154	0	0	0	3	1	0	4	0	0	0	0	0
363.67	163	152	106	0	0	0	3	1	0	2	0	0	0	0	0
363.87	440	146	159	0	0	0	1	0	0	4	0	0	0	0	0
364.17	472	151	111	0	0	0	0	0	0	1	0	0	0	0	0
364.37	676	165	111	0	0	0	0	0	0	2	0	0	0	0	0
364.57	151	90	168	0	0	0	3	1	0	4	0	0	0	0	0
364.77	192	57	128	0	0	0	1	1	0	1	0	2	0	0	0
364.97	290	56	186	0	0	0	4	0	0	2	0	1	0	0	0
365.17	384	88	152	0	0	0	0	0	0	2	0	1	0	0	0
365.37	75	70	179	0	0	0	2	0	0	1	0	0	0	0	0
365.57	65	75	193	0	0	0	4	1	0	0	0	0	0	0	0
365.87	697	183	131	0	0	0	2	1	0	1	0	0	0	0	0
366.07	532	87	168	0	0	0	1	0	0	0	0	0	0	0	0
366.27	/5	60	184	0	0	0	2	2	0	3	0	2	0	0	0
366.57	619	1//	94	0	0	0	0	0	0	3	0	1	0	0	0
300.77	325	102	1/1	0	1	0	1	0	0	4	0	10	1	0	0
367.03	088	140	07	0	1	0	5	1	0	2	0	10	1	0	0
367.03	27	114	125	0	0	0	2	0	0	3	0	4	0	0	0
367.43	131	83	159	0	0	0	2	0	0	0	0	3	0	0	0
367.63	239	91	167	0	0	0	5	1	0	4	0	2	0	0	0
367.83	185	100	111	0	0	0	5	0	0	3	0	4	1	0	0
368.08	65	63	143	0	0	0	4	2	0	6	0	0	0	0	0
368.33	86	89	106	0	0	0	1	0	0	2	0	0	0	0	0
368.58	23	68	158	0	0	0	1	0	0	2	0	0	0	0	0
368.78	24	61	132	0	0	0	0	5	0	4	0	2	0	0	0
369.08	113	65	161	0	0	0	0	0	0	0	0	3	0	0	0
369.28	54	55	147	0	1	0	1	1	0	1	0	1	0	0	0
369.43	34	112	71	0	0	0	3	0	0	2	0	6	2	0	0
369.69	55	52	181	1	0	0	7	2	0	1	0	4	0	0	0
369.88	78	38	108	0	0	0	3	0	0	1	0	1	0	0	0
370.08	282	55	107	0	0	0	0	0	0	5	0	1	0	0	0
370.38	60	64	78	0	0	0	1	1	0	1	0	5	0	0	0
370.55	9	36	115	0	0	0	14	1	0	0	0	1	0	0	0
370.8	42	41	127	2	0	0	9	7	0	1	0	1	0	0	0
371	47	42	99	0	0	0	9	1	0	1	0	1	0	0	0

					Imbilicus	imbilicus lg.	6r	·				ohus		large
	ohaera discopora	dus spp.	ofenestra haqii	ofenestra minuta	ofenestra pseudou	ofenestra pseudou	idoumbilicus w/plu	ofenestra round sp	ilithus <3 microns	lithus abies form	lithus compactus	lithus heteromorp	lithus moriformis	lithus moriformis
CCSF-A (m)	Pontosp	Pyrocyd	Reticulo	Reticulo	Reticulo	Reticulo	R. pseu	Reticulo	Spheno	Spheno	Spheno	Spheno	Spheno	Spheno
362.57	0	0	30	3	27	38	0	0	6	10	3	3	1	0
362.77	0	0	16	16	12	46	0	0	6	19	6	5	5	0
362.97	1	0	45	9	46	34	4	0	2	27	4	1	0	0
363.17	0	0	37	17	22	35	0	0	3	12	5	2	3	0
363.37	0	1	27	7	21	30	0	0	2	15	4	3	2	0
363.67	0	0	59	14	26	16	2	0	15	16	9	8	8	2
363.87	0	0	24	5	21	26	0	0	11	21	9	7	7	1
364.17	0	0	33	9	34	25	0	0	14	39	20	9	11	0
364.37	0	1	40	4	17	12	0	0	27	56	14	13	13	1
364.57	0	0	10	0	12	17	0	0	4	34	8	7	7	2
364.77	0	1	29	10	39	31	0	0	15	30	8	14	2	0
364.97	0	0	3	5	8	44	0	0	3	16	1	14	13	0
365.17	0	1	10	0	19	23	0	0	/	32	2	24	0	4
365 57	0	0	25	2	10	14	0	0	5	14	5	14 5	3	0
365.87	0	0	41	13	39	46	1	0	11	27	13	7	4	0
366.07	0	0	11	4	22	36	0	0	5	15	5	4	4	0
366.27	0	1	13	2	7	37	0	0	2	12	3	6	5	0
366.57	0	0	57	35	39	23	0	0	9	33	9	2	2	0
366.77	0	0	20	16	10	26	0	0	6	26	12	5	4	0
366.97	0	0	45	23	32	11	6	0	21	40	20	4	7	0
367.03	0	0	35	18	19	29	0	0	16	47	5	9	5	0
367.23	0	0	28	13	13	23	0	0	2	44	4	11	1	0
367.43	0	2	10	7	13	31	0	0	4	29	2	9	1	0
367.63	0	1	8	9	17	21	0	1	6	20	3	28	1	1
367.83	0	0	20	15	25	25	1	2	9	21	2	34	9	0
368.08	0	0	12	9	9	31	0	0	2	11	5	33	5	0
368.33	0	0	33	6	17	24	0	0	10	12	9	85	3	0
368.58	0	1	14	4	8	19	0	0	9	34	2	46	1	4
368.78	0	0	9	5	3	29	0	0	6	22	8	43	10	0
369.08	0	0	18	7	15	23	0	0	7	37	5	16	2	1
369.28	0	0	34	6	21	25	0	0	1	15	5	20	3	0
369.43	0	0	84	9	21	8	1	0	15	28	29	26	5	0
369.69	0	1	11	4	11	22	0	0	2	26	4	39	7	1
369.88	U	U	/ c	1	12	23 15	U	U	12	42	2	72	3	U
370.08	U	0	ס דר	1	5 11	15 27	U	0	12	33 11	5	60	ک =	1
370.38	0	0	۲/ ۱۸	D 1	10	۲/ ۸۱	0	U n	0	44 10	5 7	00 67	5 7	0
370.35	1	1	14 74	ı z	10	41 40	0	n	э 2	19	د 5	22	с С	0 N
371	0	1	19	1	12	32	0	0	4	16	4	41	5	1

CCSF-A (m)	Triquetrorhabdulus millowii	Triquerorhabdulus rioii	Umbilicosphaera rotula
362.57	0	0	0
362.77	1	0	4
362.97	0	1	1
363.17	0	0	1
363.37	0	1	1
363.67	0	0	0
363.87	0	0	4
364.17	0	1	0
364.37	0	0	0
364.57	0	0	4
364.77	0	0	0
364.97	0	0	2
365.17	0	0	2
365.37	0	0	0
365.57	0	0	0
365.87	0	0	1
366.07	1	0	0
366.27	1	0	0
366.57	0	0	3
366.77	0	0	3
366.97	0	0	1
367.03	0	1	1
367.23	0	0	0
367.43	0	0	1
367.63	0	0	0
367.83	0	0	1
368.08	0	0	0
368.33	0	0	0
368.58	0	0	0
368.78	0	0	2
369.08	0	0	3
369.28	0	0	1
369.43	0	0	0
369.69	0	0	0
369.88	0	0	1
370.08	0	0	4
370.38	0	0	0
370.55	0	0	0
370.8	1	0	4
371	0	0	3

Hole	Core	Sect.	Interval	CCSF-A (m)	Age	Etching	Overgrowth	Calcidiscus leptoporous	Calcidiscus macintyrei	Calcidiscus premacintyrei	Coccolithus miopelagicus	Coccolithus pelagicus	Coronocyclus nitescens	Coronocyclus nitescens elliptical	Cyclicargolithus floridanus
111338B	37	5	77-78	371.2	13.834	E2	02	2	0	0	0	9	1	0	1
U1338B	37	5	97-98	371.2	13 841	F2	01	1	0	1	1	12	3	0	1
U1338B	37	5	127-129	371.65	13.850	F2	01	8	0	0	4	12	0	1	5
U1338B	37	5	147-148	371.9	13.859	E2	01	4	1	0	5	12	0	0	6
U1338C	38	1	115-117	372.14	13.867	E1		1	0	0	1		1	0	3
U1338B	37	6	27-28	372.15	13.867	E1		2	0	1	0	6	0	0	1
U1338C	38	1	125-127	372.24	13.870	<e1< td=""><td></td><td>3</td><td>0</td><td>0</td><td>3</td><td>9</td><td>0</td><td>1</td><td>4</td></e1<>		3	0	0	3	9	0	1	4
U1338C	38	1	145-147	372.44	13.877	E1		3	0	0	0	22	0	0	4
U1338C	38	2	15-17	372.64	13.884	E2		3	1	2	3	19	0	1	0
U1338C	38	2	35-37	372.84	13.891	E2		5	0	0	1	20	0	0	4
U1338C	38	2	55-57	373.04	13.898	E2		5	0	3	3	9	0	0	7
U1338C	38	2	75-76	373.24	13.905	E2	01	7	0	2	11	21	0	0	6
U1338C	38	2	95-97	373.44	13.912	E2	01	6	0	1	3	19	1	0	1
U1338C	38	2	125-127	373.74	13.923	E2		2	0	1	2	28	0	0	0
U1338C	38	2	145-147	373.94	13.930	E2		4	0	1	3	24	0	1	0
U1338C	38	3	5-7	374.04	13.933	E2		5	0	1	4	13	0	1	0
U1338C	38	3	15-17	374.14	13.937	E2		5	0	4	6	30	0	0	2
U1338C	38	3	45-47	374.44	13.947	E1	01	1	0	3	5	36	0	0	3
U1338C	38	3	65-67	374.64	13.954	E2		3	0	2	9	36	0	0	3
U1338C	38	3	95-97	374.94	13.964	E2	01	4	1	2	14	33	0	0	16
U1338C	38	3	105-107	375.04	13.968	E2		5	1	1	5	31	0	2	2
U1338C	38	3	125-127	375.24	13.975	E2		5	0	2	1	89	0	0	9
U1338C	38	3	145-147	375.44	13.982	E2		12	0	2	0	67	1	1	6
U1338C	38	4	15-17	375.64	13.989	E2		8	1	2	0	62	0	0	6
U1338C	38	4	45-47	375.94	13.999	E2		3	0	0	2	59	0	0	9
U1338C	38	4	65-67	376.14	14.006	E2		4	1	2	3	44	0	2	23
U1338C	38	4	85-87	376.34	14.013	E2	01	2	0	0	1	56	0	0	16
U1338C	38	4	105-107	376.54	14.020	E2		4	0	0	4	32	0	0	38
U1338C	38	4	135-137	376.84	14.031	E2	01	6	0	1	6	34	0	1	15
U1338C	38	5	5-7	377.04	14.038	E2		2	0	0	1	26	0	0	13
U1338C	38	5	25-27	377.24	14.045	E2		5	0	2	1	47	0	1	8
U1338C	38	5	45-47	377.44	14.052	E2		6	1	3	1	56	1	1	8
U1338C	38	5	65-67	377.64	14.059	E1	01	5	0	0	2	19	0	0	13
U1338C	38	5	85-87	377.84	14.066	E1	01	5	0	0	0	35	0	0	9
U1338B	38	2	77-78	378.05	14.073	E1		3	0	1	9	45	0	0	7
U1338B	38	2	97-98	378.23	14.079	E2		5	0	0	0	50	1	0	1
U1338B	38	2	117-118	378.43	14.086	E2		0	0	2	7	61	0	0	6
U1338B	38	2	137-138	378.63	14.093	E2		2	2	1	2	56	0	0	3
U1338B	38	3	7-8	378.83	14.100	E2		0	1	0	6	43	0	0	9
U1338B	38	3	27-28	379.05	14.108	E2		4	1	0	1	37	0	0	10
CCSF-A (m)	Dictyococcities <3 microns	Dictyococcities 3-5 microns	Dictyococcities antarcticus	Discoaster deflandrei	Discoaster exilis	Discoaster pansus	Discoaster spp.	Discoaster variabilis	Hayaster perplexus	Helicosphaera burkei	Helicosphaera carteri	Helicosphaera granulata	Heliocsphaera minuta	Helicosphaera scissora	Orthorhabdus serratus
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371.2	31	28	120	0	0	0	1	1	0	0	0	0	0	0	0
371.4	41	51	88	0	0	0	5	2	0	2	0	0	0	0	0
371.65	33	96	106	1	0	0	4	0	0	2	0	2	3	0	0
371.9	57	74	146	0	0	0	2	1	0	4	0	0	0	0	0
372.14	39	138	91	0	0	0	0	1	0	2	0	1	0	0	0
372.15	117	121	124	0	0	0	1	0	0	2	0	3	0	0	0
372.24	69	247	62	0	0	0	0	1	0	3	0	9	0	0	0
372.44	72	60	168	0	0	0	0	0	0	4	0	1	0	0	0
372.64	44	64	135	0	0	0	1	1	0	0	0	0	0	0	0
372.84	108	83	149	0	0	0	0	0	0	1	0	1	0	0	0
373.04	27	36	120	0	1	0	11	1	0	1	0	1	0	0	0
373.24	47	100	65	0	0	0	7	2	0	1	0	5	0	0	0
373.44	48	51	139	0	0	0	1	0	0	1	0	2	0	0	0
373.74	34	97	71	0	0	0	3	0	0	0	0	0	0	0	0
373.94	34	34	87	0	0	0	2	1	0	0	0	6	0	0	0
374.04	56	59	77	1	0	0	3	3	0	2	0	4	0	0	0
374.14	70	61	84	2	0	0	2	0	0	0	0	7	0	0	0
374.44	227	65	74	0	0	0	1	1	0	8	0	8	0	0	0
374.64	59	51	99	0	0	0	7	3	0	2	0	4	0	0	0
374.94	13	84	52	1	3	0	17	5	0	0	0	0	0	0	0
375.04	10	100	81	0	1	0	6	6	0	0	0	0	0	0	0
375.24	31	41	69	1	0	0	13	3	0	1	0	0	0	0	0
375.44	108	47	73	0	0	0	2	0	0	1	0	1	1	0	0
375.64	96	32	105	0	0	0	13	0	0	2	0	1	0	0	0
375.94	73	87	96	0	0	0	2	2	0	2	0	4	0	0	0
376.14	34	35	98	0	0	0	3	1	0	3	0	/	0	0	0
376.34	116	64	104	1	0	0	3	0	0	5	0	0	0	0	0
370.34	165	40	104	0	3	0	15	5	0	2	0	10	0	0	0
370.04	74	10	107	0	0	0	4	1	0	2	0	10	2	0	0
277.04	14	42	107	0	0	0	4	1	0	4	0	4	0	0	0
377.24	86	42 80	101	3	0	0	2	1	0	2	0	1	0	0	0
377.44	130	133	55	0	0	0	2	2	0	2	0	1 2	1	0	0
377.04	133	96	65	0	0	0	2	2 1	0	0	0	2	0	0	0
378.05	29	62	30	3	0	0	11	4	0	2	0	4	0	0	0
378.23	48	59	63	0	0	0	2	0	0	0	0	2	0	0	0
378.43	34	28	82	1	0 0	ñ	-	1	ñ	8	ũ	3	ñ	ñ	ñ
378.63	140	117	101	1	0	0	1	0	0	1	0	5	0	0	0
378.83	185	55	117	- 7	0	0	10	0	0	-	0	- 4	0	0	0
379.05	172	77	65	3	0	0	8	0	0	3	0	2	1	0	0

					ilicus	ilicus lg.						<i>(</i> 2		ē
	ohaera discopora	clus spp.	ofenestra haqii	ofenestra minuta	ofenestra pseudoumb	ofenestra pseudoumb	udoumbilicus w/plug	ofenestra round sp.	olithus <3 microns	viithus abies form	olithus compactus	olithus heteromorphus	olithus moriformis	olithus moriformis larg
CCSF-A	ontosl	/rocy(	eticulo	eticulo	eticulo	eticulo	. pser	eticulo	phenc	phenc	phenc	phenc	phenc	phenc
(m)	ā o	é.	22 10	~	19	21	~	ě.	ທ 1 ວ	ى ەد	S A	ر م	S S	ى م
371.2	0	0	28	4	27	43	1	0	6	19	4	90 49	11	0
371.65	0	0	47	7	27	24	1	0	8	27	4	20	3	0
371.9	0	1	20	1	13	31	0	1	1	15	3	39	11	0
372.14	0	1	35	0	33	19	0	0	23	39	9	62	6	0
372.15	0	0	36	5	7	26	0	0	33	30	9	29	6	5
372.24	0	0	70	14	22	20	13	0	28	38	20	65	8	0
372.44	0	0	20	3	6	29	0	4	6	22	1	24	0	1
372.64	0	0	39	1	17	32	0	3	2	6	8	29	5	0
372.84	0	1	20	3	9	19	0	1	13	21	7	35	9	0
373.04	0	0	46	12	24	25	0	1	3	3	7	36	10	0
373.24	0	0	48	9	29	37	4	0	9	4	8	44	3	2
373.44	0	0	21	5	10	38	0	1	3	9	3	38	5	1
3/3./4	0	0	68	15	31	20	1	1	2	/	2	59	2	1
373.94	0	0	28	6	10	42 51	0	3	4	2	3	88	13	2
374.04	0	0	22	11	27	47	0	0	5	5	3	46	12	1
374.44	0	0	36	7	15	38	0	0	11	16	1	43	9	3
374.64	0	0	15	11	20	34	0	0	5	6	4	47	10	2
374.94	0	0	75	3	18	5	1	0	3	5	7	40	3	4
375.04	0	0	83	20	24	5	1	0	6	11	1	35	2	0
375.24	0	0	32	4	21	17	0	1	0	8	4	26	5	0
375.44	0	0	26	10	13	10	0	0	3	5	6	58	12	1
375.64	0	0	20	11	12	17	0	1	4	4	0	37	5	0
375.94	0	0	50	12	18	14	0	0	7	20	8	24	1	0
376.14	0	1	12	3	20	31	0	0	2	12	5	21	7	0
376.34	0	0	26	1	28	29	0	1	7	27	5	25	2	2
376.54	0	1	35	8	23	23	0	1	8	3	2	16	7	0
376.84	5	0	41	11	26	11	4	0	12	10	4	52	5	3
377.04	2	0	10	2	3 10	48	0	0	2	1	1	22	ð F	0
377.24	0	0	14	4	19	30	0	0	2	2	5	41	2	0
377.64	0	0	63	49	12	21	3	0	12	0	18	73	3	3
377.84	0	0	37	34	20	23	1	2	7	14	6	100	8	1
378.05	0	0	39	12	13	28	0	1	9	9	7	65	5	0
378.23	0	0	33	8	3	22	0	3	3	4	6	102	15	0
378.43	0	0	16	4	5	15	0	2	1	2	7	61	5	1
378.63	0	0	39	11	11	12	0	4	4	17	3	59	5	2
378.83	0	1	42	7	5	10	0	0	7	6	3	22	6	0
379.05	0	0	70	13	13	9	0	4	6	29	1	34	2	0

CCSF-A (m)	Triquetrorhabdulus millowii	Triquerorhabdulus rioii	Umbilicosphaera rotula
371.2	0	0	0
371.4	0	0	2
371.65	0	0	1
371.9	0	0	2
372.14	0	0	0
372.15	0	0	3
372.24	1	1	2
372.44	0	0	1
372.64	0	0	2
372.84	0	0	4
373.04	0	0	1
373.24	0	0	2
373.44	0	0	1
373.74	0	0	2
373.94	0	0	7
374.04	0	0	4
374.14	0	0	8
374.44	0	1	6
374.64	1	0	2
374.94	0	0	0
375.04	0	0	1
375.24	0	0	0
375.44	0	0	0
375.64	0	0	5
375.94	1	1	6
376.14	0	0	3
376.34	0	0	3
376.54	1	0	1
376.84	0	0	5
377.04	0	1	9
377.24	0	0	5
377.44	0	0	9
377.64	0	0	22
377.84	0	0	5
378.05	0	0	14
378.23	1	0	5
378.43	0	0	11
378.63	0	0	8
378.83	0	0	5
379.05	0	0	5

Hala	Corro	Sort	Interval	CCSF-A	400	tching	vergrowth	alcidiscus leptoporous	alcidiscus macintyrei	alcidiscus premacintyrei	occolithus miopelagicus	occolithus pelagicus	oronocyclus nitescens	coronocyclus nitescens elliptical	yclicargolithus floridanus
поне	Core	Sect.		(111)	Age	ш	0	0	0	0	0	0	0	0	0
U1338B	38	3	47-48	379.23	14.114	E2	01	3	0	1	5	28	1	0	2
013300	20	2	07-00	270.62	14.121	L2 52	01	2	1	1 2	4	16	1	0	6
U1338B	38	2	107-108	379.03	14.126	E2	01	2	1	2	7 3	76	0	0	8
U1338B	38	3	127-128	380.03	14.130	F1	01	4	0	1	3	86	0	0	4
U1338B	38	3	147-148	380.23	14,149	F1		0	0	0	8	87	0	0	8
U1338B	38	4	17-18	380.45	14 156	F1		3	2	1	2	98	0	1	0
U1338B	38	4	37-38	380.63	14,163	F1		4	0	1	0	85	0	0	2
U1338B	38	4	57-58	380.83	14.170	E1		8	0	2	0	85	0	0	1
U1338B	38	4	77-78	381.03	14.177	E1		5	0	0	1	88	2	0	2
U1338B	38	4	107-108	381.35	14.188	E1	01	1	0	0	0	138	0	0	7
U1338B	38	4	127-128	381.53	14.194	E1		6	0	0	3	81	0	0	5
U1338B	38	4	147-148	381.73	14.201	E1		2	0	0	2	107	0	0	3
U1338B	38	5	17-18	381.95	14.209	E1	01	2	0	3	0	79	0	0	1
U1338B	38	5	37-38	382.13	14.215	E1		3	0	1	0	80	0	0	1
U1338B	38	5	57-58	382.35	14.223	E1		5	0	3	0	76	0	0	3
U1338C	39	2	5-7	382.55	14.230	E1	01	0	0	0	0	58	0	0	1
U1338C	39	2	15-17	382.65	14.233	E1		6	0	1	0	54	0	0	2
U1338C	39	2	35-37	382.85	14.240	<e1< td=""><td></td><td>4</td><td>0</td><td>3</td><td>1</td><td>70</td><td>0</td><td>0</td><td>3</td></e1<>		4	0	3	1	70	0	0	3
U1338C	39	2	45-47	382.95	14.244	E1		3	0	0	0	114	0	0	2
U1338C	39	2	65-67	383.15	14.251	E1		1	0	0	0	76	0	0	1
U1338C	39	2	95-97	383.45	14.261	E1		1	0	0	1	59	0	0	4
U1338C	39	2	115-117	383.65	14.268	E2		1	0	0	0	47	0	0	2
U1338C	39	2	135-137	383.85	14.275	E1		9	0	2	1	66	0	0	1
U1338C	39	3	5-7	384.05	14.282	E1		5	0	1	3	40	0	0	0
U1338C	39	3	25-27	384.25	14.289	E1		5	0	1	3	61	0	0	3
U1338C	39	3	45-47	384.45	14.296	E1		6	0	0	6	31	1	0	4
U1338C	39	3	65-67	384.65	14.303	E1		3	1	0	2	23	0	0	2
U1338C	39	3	95-97	384.95	14.313	<e1< td=""><td></td><td>7</td><td>2</td><td>2</td><td>15</td><td>40</td><td>0</td><td>0</td><td>6</td></e1<>		7	2	2	15	40	0	0	6
U1338C	39	3	115-117	385.15	14.320	E1		6	0	1	6	25	0	1	8
U1338C	39	3	135-137	385.35	14.327	E2		2	0	2	13	25	0	0	16
U1338C	39	4	15-17	385.65	14.338	<e1< td=""><td>01</td><td>5</td><td>0</td><td>0</td><td>1</td><td>11</td><td>0</td><td>0</td><td>4</td></e1<>	01	5	0	0	1	11	0	0	4
U1338C	39	4	35-37	385.85	14.345	E1		6	0	2	3	31	0	0	12
U1338C	39	4	45-55	385.95	14.348	E2	01	3	0	0	8	28	0	0	22
U1338C	39	4	75-77	386.25	14.359	E1		11	1	0	3	27	0	0	2
U1338C	39	4	95-97	386.45	14.366	E1	01	8	0	0	19	37	0	0	14
U1338C	39	4	115-117	386.65	14.373	E1		9	0	3	13	48	0	0	16
U1338C	39	4	135-137	386.85	14.379	E2	01	4	0	0	15	16	0	0	10
U1338C	39	5	15-17	387.15	14.390	E2		10	2	0	4	13	1	0	1
U1338C	39	5	43-45	387.43	14.400	E1	01	2	0	0	11	31	0	1	24

CCSF-A (m)	Dictyococcities <3 microns	Dictyococcities 3-5 microns	Dictyococcities antarcticus	Discoaster deflandrei	Discoaster exilis	Discoaster pansus	Discoaster spp.	Discoaster variabilis	Hayaster perplexus	Helicosphaera burkei	Helicosphaera carteri	Helicosphaera granulata	Heliocsphaera minuta	Helicosphaera scissora	Orthorhabdus serratus
379.23	112	69	77	4	0	0	7	2	0	9	0	12	7	0	0
379.43	149	74	81	5	2	0	5	0	0	5	0	1	0	0	0
379.63	108	23	93	5	0	0	6	0	0	11	0	13	0	0	0
379.85	89	54	80	2	1	0	4	0	0	2	0	7	2	0	0
380.03	177	59	56	1	0	0	13	3	0	8	0	2	0	0	0
380.23	70	52	75	5	0	0	7	0	0	9	0	1	0	0	0
380.45	99	67	78	0	0	0	2	0	0	4	0	0	0	0	0
380.63	82	122	96	1	0	0	1	1	0	2	0	0	0	0	0
380.83	132	112	98	1	0	0	1	0	1	5	0	1	0	0	0
381.03	41	78	83	3	0	0	6	4	0	8	0	4	0	0	0
381.35	82	65	27	0	0	0	10	0	0	2	0	1	0	0	0
381.53	97	109	29	0	0	0	2	2	1	10	0	0	0	0	0
381.73	107	101	74	1	0	0	5	0	0	2	0	5	0	0	0
381.95	147	207	23	0	0	0	2	0	0	0	0	5	1	0	1
382.13	85	81	54	0	0	0	1	0	0	2	0	0	0	0	0
382.35	219	70	42	0	0	0	4	0	0	6	0	3	0	0	0
382.55	214	193	42	0	1	0	0	0	0	0	0	5	0	0	0
382.65	126	110	31	0	0	0	3	0	0	2	0	2	0	0	0
382.85	202	129	35	0	0	0	2	0	0	1	0	3	0	0	0
382.95	152	103	62	0	0	0	5	2	0	0	0	4	0	1	0
383.15	563	50	44	0	0	0	2	0	0	1	0	1	0	0	0
383.45	295	77	13	0	0	0	0	0	0	3	0	1	0	0	0
383.65	354	147	64	1	0	0	3	0	0	2	0	1	0	0	0
383.85	230	77	62	1	0	0	5	0	0	5	0	4	0	0	0
384.05	534	167	42	0	0	0	3	2	0	1	1	2	1	0	0
384.25	462	165	45	0	0	0	5	1	0	12	0	4	1	0	0
384.45	3/2	229	40	0	0	0	3	0	0	2	0	5	0	0	0
384.65	86	/0	94	4	0	0	11	2	0	0	0	0	0	0	0
384.95	217	170	109	1	0	0	3 6	2	0	1	0	5	0	0	0
305.15	150	125	108	4	0	0	6 F	1	0	4	0	2	0	0	0
205.22	152	125	102	0	0	0	כ ר	1	0	2	0	1	0	0	0
385 85	118	100	102	1	0	0	2	1	0	2	0	12	0	0	0
205.02	00	170	107	1	0	0	2	1	0	0	0	12	0	0	0
386.25	144	176	145	1 0	n	n	1	L L	n	9 4	n	1	1	n	n
386.45	68	221	114	1	2	0	5	4	0	5	0	۰ ۵	1	0	0
386.65	51	173	67	- 0	<u>د</u> ۱	n	3	0	n	4	0	15	0	n	0
386.85	17	70	126	4	n	ñ	5	4	ñ	4	ñ	16	ñ	ñ	n
387.15	113	249	147	0	0	Ũ	0	0	Ũ	4	0	5	0	0	0
387.43	89	121	130	0	0	0	5	1	0	4	0	0	0	0	0

	liscopora		a haqii	a minuta	a pseudoumbilicus	a pseudoumbilicus lg.	licus w/plug	a round sp.	3 microns	oies form	ompactus	eteromorphus	ioriformis	loriformis large
	ohaera c	dds snþ	ofenestr	ofenestr	ofenestr	ofenestr	doumbi	ofenestr	lithus <	lithus a	lithus co	lithus h	lithus m	lithus m
CCSF-A (m)	Pontosp	Pyrocyc	Reticulo	Reticulo	Reticulo	Reticulo	R. pseu	Reticulo	Spheno	Spheno	Spheno	Spheno	Spheno	Spheno
379.23	0	0	49	26	10	13	0	4	0	17	6	39	12	0
379.43	0	0	42	4	16	21	0	4	7	31	9	32	5	0
379.63	0	0	13	8	11	27	0	3	1	13	5	21	10	1
379.85	0	0	26	12	5	6	1	7	4	13	6	36	3	3
380.03	0	0	41	26	6	2	0	0	2	16	10	30	7	0
380.23	0	0	23	1	6	15	0	1	4	5	7	29	10	0
380.45	0	0	43	5	10	10	0	1	1	7	3	29	3	1
380.63	0	0	49	10	13	9	0	0	5	6	1	22	6	0
380.83	0	1	50	4	7	15	0	0	2	7	3	14	7	2
381.03	1	0	29	6	7	24	0	0	4	11	4	26	7	3
381.35	0	0	73	23	6	12	0	1	1	4	1	16	3	1
381.53	0	0	109	24	5	1/	0	0	0	5	4	9	4	2
381.73	0	0	144	16	10	15	0	3	1	12	0	12	4	1
202.12	0	0	144	0	9	9	0	0	1	15	с С	13	1	2
382 35	0	0	108	16	5	12	0	1	2	2	1	14	7	1
382.55	0	0	132	32	9	12	0	1	6	14	1	14	1	2
382.65	0	0	137	7	18	22	0	1	2	3	4	9	4	0
382.85	0	0	162	63	2	1	0	4	5	5	4	17	5	0
382.95	0	0	65	36	7	3	0	0	2	6	4	38	3	4
383.15	0	0	130	35	5	10	0	0	0	6	0	15	7	0
383.45	1	0	162	22	13	9	0	1	3	16	1	12	2	2
383.65	0	0	127	15	9	8	0	2	0	6	3	18	4	0
383.85	0	0	116	37	4	7	0	0	3	4	0	15	3	0
384.05	0	0	155	54	8	6	0	2	0	0	3	16	5	1
384.25	1	0	107	46	7	10	0	1	1	5	1	10	9	1
384.45	0	0	168	52	3	2	0	2	4	6	3	15	1	0
384.65	0	0	109	9	9	13	0	3	0	4	1	10	3	1
384.95	0	0	150	161	24	0	0	7	5	10	6	10	5	0
385.15	0	0	82	22	5	7	0	2	0	6	2	17	7	0
385.35	0	0	45	20	10	27	0	0	1	13	2	13	2	0
385.65	0	0	128	61	12	14	1	1	6	5	4	28	3	0
385.85	1	1	69	41	5	32	0	1	2	15	3	11	/	1
385.95	1	0	26	15	16	17	0	1	1	15	3	15	/	0
386 45	0	1	30 62	17 25	72 01	13 14	0	4	1	10	3 1	10	ט ר	U N
386 65	n	1 0	59	6	12	 21	n	ے م	י ז	6	1 2	17	5	n
386-85	0	n	26	2	9	44	0	n	2	3	<u>د</u> 1	8	4	1
387.15	0	2	49	0	28	7	0	3	2	7	1	12	5	-
387.43	0	0	34	18	17	15	0	10	3	7	0	6	0	0

CCSF-A (m)	Triquetrorhabdulus millowii	Triquerorhabdulus rioii	Umbilicosphaera rotula
379.23	1	0	5
379.43	1	0	3
379.63	0	0	7
379.85	0	0	7
380.03	0	0	9
380.23	2	0	9
380.45	0	0	4
380.63	0	0	1
380.83	0	0	6
381.03	0	0	6
381.35	0	0	1
381.53	0	0	11
381.73	0	0	1
381.95	0	0	8
382.13	0	0	11
382.35	0	0	7
382.55	1	0	6
382.65	0	0	2
382.85	0	0	5
382.95	0	0	5
383.15	0	0	3
383.45	0	0	5
383.65	0	0	3
383.85	0	0	2
384.05	0	0	4
384.25	0	0	7
384.45	0	0	3
384.65	0	0	8
384.95	0	0	2
385.15	0	0	3
385.35	0	0	4
385.65	0	0	0
385.85	0	0	2
385.95	0	0	0
386.25	0	0	4
386.45	0	0	1
386.65	U	U	4
386.85	U	U	1
307.15	U	U	3 n
201.43	U	U	2

Hole	Core	Sect.	Interval	CCSF-A (m)	Age	Etching	Overgrowth	Calcidiscus leptoporous	Calcidiscus macintyrei	Calcidiscus premacintyrei	Coccolithus miopelagicus	Coccolithus pelagious	Coronocyclus nitescens	Coronocyclus nitescens elliptical	Cyclicargolithus floridanus
U1338C	39	5	65-67	387.65	14.407	E1		7	0	0	6	33	0	0	3
U1338C	39	5	85-87	387.85	14.414	E2		4	1	2	5	37	3	5	4
U1338C	39	5	115-117	388.15	14.425	<e1< td=""><td></td><td>6</td><td>0</td><td>2</td><td>30</td><td>37</td><td>0</td><td>2</td><td>8</td></e1<>		6	0	2	30	37	0	2	8
U1338C	39	5	135-137	388.35	14.432	E1		5	0	3	7	41	1	0	6
U1338C	39	6	5-7	388.55	14.439	E1		5	0	0	5	43	2	2	6
U1338C	39	6	35-37	388.85	14.449	E1		2	0	0	4	32	1	0	15
U1338C	39	6	55-57	389.05	14.456	E1	01	4	0	0	2	32	0	1	6
U1338C	39	6	75-77	389.25	14.463	E2		10	0	1	2	17	3	0	3
U1338C	39	6	95-97	389.45	14.470	E2	01	1	0	1	2	26	0	0	2
U1338C	39	6	125-127	389.75	14.481	E1	01	8	0	0	3	12	1	0	5
U1338C	39	6	145-147	389.95	14.487	E1		6	0	1	4	28	0	1	5
U1338C	39	7	15-17	390.15	14.494	E2		3	0	0	3	21	0	2	2
U1338C	39	7	35-37	390.35	14.501	E1		7	1	0	6	29	0	2	7
U1338C	39	7	65-67	390.65	14.512	E1		5	0	2	5	17	0	1	5

CCSF-A (m)	Dictyococcities <3 microns	Dictyococcities 3-5 microns	Dictyococcities antarcticus	Discoaster deflandrei	Discoaster exilis	Discoaster pansus	Discoaster spp.	Discoaster variabilis	Hayaster perplexus	Helicosphaera burkei	Helicosphaera carteri	Helicosphaera granulata	Heliocsphaera minuta	Helicosphaera scissora	Orthorhabdus serratus
387.65	142	103	129	1	0	0	9	6	0	1	0	6	1	0	0
387.85	99	170	75	1	0	0	10	1	0	11	0	19	1	0	0
388.15	113	165	88	0	0	0	2	2	0	0	0	10	0	1	0
388.35	105	178	116	0	0	0	6	0	0	11	0	2	4	0	0
388.55	127	139	83	2	0	0	2	0	0	8	0	3	0	0	0
388.85	95	254	48	0	1	0	0	0	0	5	0	9	1	0	0
389.05	67	186	124	0	0	0	3	0	0	1	0	4	0	0	0
389.25	58	121	86	0	0	0	1	0	0	1	0	1	0	0	0
389.45	42	91	91	0	0	0	1	0	0	2	0	2	0	0	0
389.75	119	168	68	0	0	0	1	0	0	0	0	4	0	0	1
389.95	51	81	132	2	0	0	2	1	0	3	0	1	0	0	0
390.15	43	191	54	2	0	0	10	0	0	0	0	1	0	0	1
390.35	16	58	113	0	0	0	6	2	0	8	0	7	0	0	0
390.65	4	21	33	3	2	0	29	13	0	0	0	2	0	0	0

CCSF-A (m)	Pontosphaera discopora	Pyrocyclus spp.	Reticulofenestra haqii	Reticulofenestra minuta	Reticulofenestra pseudoumbilicus	Reticulofenestra pseudoumbilicus large	Reticulofenestra pseudoumbilicus w/plug	Reticulofenestra round sp.	Sphenolithus <3 microns	Sphenolithus abies form	Sphenolithus compactus	Sphenolithus heteromorphus	Sphenolithus moriformis	Sphenolithus moriformis large
387.65	0	0	32	25	15	17	0	2	0	2	1	21	11	0
387.85	0	0	17	8	8	44	0	4	0	10	2	25	5	2
388.15	0	0	103	26	33	6	0	1	9	0	0	24	13	1
388.35	0	1	20	6	13	24	0	3	1	1	1	26	5	2
388.55	0	0	15	17	24	58	0	3	2	8	1	32	6	0
388.85	1	0	103	30	6	0	3	2	10	12	11	69	5	2
389.05	0	1	19	16	12	28	1	0	7	8	1	45	8	4
389.25	0	0	35	16	12	28	0	0	4	4	3	81	11	0
389.45	0	0	23	8	9	10	0	0	1	7	3	95	10	1
389.75	0	0	33	22	12	14	0	0	5	7	10	121	11	4
389.95	0	0	27	9	3	8	0	0	3	2	3	57	12	0
390.15	0	0	79	15	44	13	1	1	9	22	9	34	8	0
390.35	0	0	24	2	17	46	0	0	2	7	4	24	6	0
390.65	0	0	144	5	23	0	0	1	2	0	10	40	6	0

CCSF-A (m)	Triquetrorhabdulus millowii	Triquerorhabdulus rioii	Umbilicosphaera rotula
387.65	1	0	2
387.85	0	4	2
388.15	1	0	3
388.35	4	0	1
388.55	0	0	0
388.85	0	0	0
389.05	0	0	1
389.25	0	0	1
389.45	0	0	4
389.75	0	0	3
389.95	3	0	0
390.15	0	0	1
390.35	0	1	2
390.65	0	0	0

# VITA

## Leah Jill Schneider

#### Education

2006-12	Pennsylvania State University, Ph.D in Geosciences Advisors: Dr. Timothy Bralower and Dr. Lee Kump
2002-06	University of Nebraska-Lincoln, B.S. in Geology Graduated with Distinction and Honors, GPA 3.752

Advisor: Dr. David Watkins

#### Experience

2009	Nannofossil biostratigrapher on IODP Leg 321, May-July
2007-08	Co-chair of the Geosciences Department Colloquium
2006	Internship with CHRONOS program, Iowa State University
2002-05	Lab Assistant for Dr. David Watkins, UNL

#### **Selected Grants**

2010-12	IODP Post-cruise funding
2010	Shell Research Facilitation Award
2006	L. Austin Weeks Grant from the American Association of Petroleum
	Geologists
2004-06	UCARE Grant from the University of Nebraska-Lincoln

#### Selected Scholarships and Honors

	<b>▲</b>
2010	ConocoPhillips Fellowship
2009	Schlanger Fellowship, Ocean Leadership
2006	Anne C. Wilson Fellowship, PSU
2005	Department of Geosciences Outstanding Undergraduate Student
2004-05	Edward J. Hirsch Scholarship-Geosciences Department
2002-06	University of Nebraska-Lincoln Regent's Scholarship
2002-06	UNL Nebraska Top Scholars
	-

#### Teaching

hematics

#### Publications

*Schneider, L.J.*, Bralower, T.J., and Kump, L.R., 2011, Response of nannoplankton to early Eocene ocean destratification. *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 310, 152-162. doi:10.1016/j.palaeo.2011.06.018

Paelike, H., Lyle, M., Nishi, H., Raffi, I., Gamage, K., Klaus, A., and *the Expedition 320/321 Scientists*, 2011, Proceedings of the Integrated Ocean Drilling Program, v 320/321.