Antarctic plant and phytoplankton response to the first phase of the Mid Miocene Climatic Optimum at South McMurdo Sound

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ANTARCTIC PLANT AND PHYTOPLANKTON RESPONSE TO THE FIRST 
PHASE OF THE MID MIOCENE CLIMATIC OPTIMUM AT SOUTH 
MCMURDO SOUND

A Thesis

Submitted to the Graduate Faculty of the 
Louisiana State University and 
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In 
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By 
Lee R. Foersterling 
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Abstract

The Antarctic Drilling Program (ANDRILL) recovered 1138.54 m of sub-seafloor marine sediments with 98% core recovery at the AND2-2A drill site in South McMurdo Sound. Biostratigraphy, magnetostratigraphy, and isotopic dating (Acton et al., 2008) indicated that an Early to Middle Miocene section (223-1138.54 mbsf) was recovered. This study focuses on an interval with high concentrations of palynomorphs, located between 460.57 and 403.48 mbsf and dated to 16.7 Ma to 16.2 Ma according to the updated Acton et al. (2008) ANDRILL SMS age model. Palynological results show a pronounced increase in organic microfossils between 434.01 and 431.91 mbsf, compared to levels recorded in underlying lower Miocene samples. In addition to the rich pollen and dinoflagellate cysts recovered within this 4-m interval, a single grain of the freshwater algae belonging to the family of Zygnemataceae was recovered at 431.91 mbsf, indicating that some fresh-water was pooling on the surface. The unusually rich samples are mainly characterized by a pronounced increase in pollen of Nothofagidites spp. and Podocarpidites spp., and spores of the mosses Coptospora sp. and Rhoipites sp. This assemblage is coincident with an increase in relative abundance of various dinoflagellate cysts, mainly Operculodinium centrocarpum and Labyrinthodinium truncatum, and the acritarchs Leiosphaeridia, Mecsekia sp, and Cymatiosphera sp. These marine and terrestrial palynomorphs indicate a peak warming period for the first phase of the Mid Miocene Climatic Optimum at 16.5 Ma only matched in intensity by younger AND2-2A sediments at 312 – 310 mbsf, dated to 15.7 – 15.5 Ma (Warny et al., 2009). However, the terrestrial signal is significantly higher at 434 – 431 mbsf compared to the
marine dominated assemblages at 310 mbsf implying that the climatic changes were more strongly felt on land than in the surface waters. We propose that this palynological signal reflects the amelioration of the paleoclimate in Antarctica during the first peak of the Middle Miocene Climatic Optimum as recorded in the Zachos et al. (2008) oxygen isotope curve.
Chapter 1. Introduction

1.1 South McMurdo Sound (ANDRILL SMS) Project Overview

Due to growing concerns for earth’s climate, there has been extensive research in the Antarctic region to uncover the precise timing and intensity of past climate changes in order to help better predict future climate evolution. The Antarctic ice sheets respond sensitively to global climate changes, and the sedimentary deposits of the Antarctic region recorded past fluctuations. The ANDRILL SMS project (AND2-2A), funded in the U.S. by the National Science Foundation, is a multination collaboration between Italy, Germany, New Zealand, and the U.S. Over 200 scientists, educators, students, drillers, and technicians from around the world are combining efforts to uncover Antarctica’s geologic history and records of climate change. The site is located 25 km west of the U.S. McMurdo Station on the eastern edge of the Ross Sea in the South McMurdo Sound (SMS), which runs between Ross Island and the Transantarctic Mountains (Figure 1).

The ANDRILL SMS team drilled through a sea-ice platform, and penetrated through 800 meters of water before reaching the sea floor where cores were collected up to 1138 meters below sea floor (mbsf) with an outstanding 98% recovery rate. The SMS core recovered sediments spanning the early to middle Miocene, with a bottom core age of 20 Ma. The core is currently being studied by scientists from many disciplines to improve our understanding of the Antarctic region’s role and evolution during the Cenozoic climate changes. Studying palynomorph (organic-walled microfossil) assemblages from samples processed from the ANDRILL SMS cores is one of these fundamental research projects needed to better constrain the evolution of climate during
the Miocene. Specifically, this thesis focuses on the climatic and oceanographic changes that occurred during a warm phase of the Middle Miocene Climatic Optimum (18–15 Ma). The detailed palynological analyses conducted on phytoplankton assemblages revealed new information on sea-surface conditions, while pollen, spore and freshwater algae provide clues into past climatic changes inferred from changes in land vegetation.

Figure 1: Location of the AND2-2A SMS drill site from a modified satellite image (NASA). Nearby volcanoes active during the Cenozoic are indicated with red circles. Note the drill site’s proximity to the Transantarctic Mountains from which location the majority of sediments and plant material were derived.
1.2 Geologic Background

The SMS location (Figure 2) lies at the southern edge of the Victoria Land Basin (VLB), an extensional rift basin composed of a series of glacial tills and diamictites. The basin receives sediment from the West Antarctic Ice Sheet via the Ross Ice Shelf and from the larger East Antarctic Ice Sheet through the Transantarctic Mountains. The West Antarctic Rift System created extensional forces that produced the north-south trending normal fault resulting in the downthrown VLB block with respect to the uplifted Transantarctic Mountains (Muller et al., 2007). The rifting generated a volcanic province to the south and east of the VLB, which provides an excellent $^{40}\text{Ar}/^{39}\text{Ar}$-dating source (Di Vencenzo et al., 2009), allowing accurate age control for the ANDRILL core.

Figure 2: Conceptual rendering showing the AND2-2A drill site location with respect to the geology of the region in the Victoria Land Basin (VLB) on the eastern downthrown block of a N-S trending normal fault (from SMS Science Team).
Following the Eocene/Oligocene transition, the climate of the Cenozoic underwent a general cooling trend evident in $\delta^{18}$O isotopic data (Shackleton and Kennett, 1975; Zachos et al., 2008). Widespread glaciation has prevailed on Antarctica presumably since the beginning of the Oligocene, 33.9 Ma. The causes for this dramatic event are still controversial. Some propose declining atmospheric CO$_2$ (DeConto and Pollard, 2003) as a major factor, while others propose that this major event is primarily the result of the opening of southern gateways that allowed for the development of the Circum Antarctic Current (Shackleton and Kennett, 1975; Anderson et al., submitted). Some recent DSDP deep-sea drilling in the Southern Ocean south of Australia and New Zealand confirmed that the Circum Antarctic Current developed about 34 million years ago when final separation occurred between Antarctica and the continental South Tasman Rise (Kennett et al., 1975). It is generally agreed that the creation of the Antarctic Circumpolar Current brought moisture to the continent in addition to isolating the continent from warm equatorial currents (Lyle et al., 2007). But the quantitative role played by these two components (atmospheric-CO$_2$ vs. oceanic-Tasman sea opening) is still debated.

1.3 Mid Miocene Climatic Optimum Background

If most post-Eocene evidence from Antarctica points toward the existence of extensive ice-sheet cover, questions have been posed regarding a specific warm period within the Cenozoic. The so-called Mid Miocene Climatic Optimum (MMCO) is a warming event that occurred in the middle of the Cenozoic general cooling trend that began around 17 Ma and ended with a rapid cooling period 14.5 – 12 Ma. The southern polar regions endured a final warm interval that preceded a shift towards dry, glacially
dominated late Neogene and Quaternary periods after 14 Ma (Naish et al., 2007). The primary evidence for this warm event is found in the $\delta^{18}$O records from benthic foraminifera from drilling projects around the world (Shackleton and Kennett, 1975; Miller et al., 1987, Zachos et al., 2008). These records show that the MMCO is associated with rapid global sea-level fluctuations during an interval of high eustatic levels (Haq, 1987), terrestrial and marine faunal changes, and plate tectonic activity (African-Eurasian plate collision) effecting global ocean currents. The $\delta^{18}$O benthic foram value at 18 Ma (prior to the warming) averaged 2.4 $^{0}/_{00}$ (PDB) with a maximum of 2.6 $^{0}/_{00}$ during the relatively stable Early Miocene (Zachos et al., 2008). At 16.5 Ma, the $\delta^{18}$O values decreased to 1.4 $^{0}/_{00}$, representing the first phase of warming during the MMCO. A brief increase of 0.8 $^{0}/_{00}$ (PDB) is then observed at ~16.2 Ma followed by the second warming phase of the MMCO from 16 – 14.8 Ma (Zachos et al., 2008). The subsequent increase of >1 $^{0}/_{00}$ in $\delta^{18}$O from 14.8 – 12 Ma indicates a rapid cooling phase associated with ice volume expansion following the end of the MMCO (Figure 3).

Because the ANDRILL SMS cores recovered sediments from the Early to Middle Miocene (from 1138 – 232 mbsf), this section provides the most complete Miocene sequence recovered to date in Antarctica and sampled both phases of the MMCO. Thus, it can potentially provide, for the first time, a set of data that can shed light into environmental conditions on and around Antarctica during the entire time period of the Mid Miocene Climatic Optimum. During the MMCO, several sequences around the world document the spread of tropical to subtropical marine and terrestrial fauna. Such evidence was presented in Hornibrook’s (1992) summary of marine Cenozoic paleoclimates in New Zealand showing the warmest biological indicators since the
middle Eocene are found during the MMCO. Similar evidence in the Northern Hemisphere of tropical-fauna migrations to higher latitudes are known from deposits in Japan (Tsuchi, 1990) proving that the MMCO had a global effect. From 17 – 14 Ma, during the MMCO, large-scale global sea-level fluctuations occurred as well, with highstands followed by ~50 meter drops in relative sea level. Following the warming, a general cooling trend occurred, with various effects including a transition from wet- to cold-based glacial regime in the Ross Sea region (Lewis et al., 2007), stabilization and growth of the EAIS, and increased aridification of mid-latitude regions (Flower and Kennett, 1993). The aridification of mid-latitude regions most likely led to the rise of grasses (Berggren and Van Couvering, 1974) and subsequently the evolution of grazing animals.

Figure 3: Zachos (2008) curve showing $\delta^{18}O$ values during the Cenozoic compiled from benthic and planktonic foraminifera from ODP and DSDP sites around the world. Note the estimated ice-free temperature index assumes an ice-free ocean and applies to a pre-glaciated Antarctica prior to 35 Ma. The Mid Miocene Climatic Optimum is highlighted in yellow and the 460 – 400 mbsf interval that is the topic of this thesis is outlined in red. It is correlated with the first phase of the MMCO from 17 – 16 Ma.
The causes for the MMCO remain disputed, but some evidence points towards changes in deep-sea circulation between the Tethys Ocean – Northern Indian Ocean and the Southern Component Waters surrounding Antarctica. Such effects are seen through a comparison of carbon isotopic evidence from deep waters in the Pacific and Atlantic oceans where $\delta^{13}C$ foram evidence in the Atlantic exhibit more positive values (Wright et al., 1992). The warm, saline deep-water source from the Tethys Ocean transported heat and moisture through upwelling into the Southern Ocean surrounding Antarctica (Woodruff and Savin, 1989, 1991). Restrictions on ocean currents through the Indonesian seaway as a result of plate tectonics likely contributed to an increased influx of warm, saline deep waters into the Southern Ocean (Kennett et al., 1985). Such oceanic circulation changes possibly contributed towards increases in moisture to the Antarctic region fostering growth of the East Antarctic Ice Sheet. This increase in heat and moisture is evident in the Antarctic biostratigraphy with increases in biological activity during the Early-Middle Miocene and through $\delta^{18}O$ evidence (Shackleton and Kennett 1975; Miller et al., 1987).

The subsequent cooling following the climax of the warm event likely resulted from the termination of the warm, saline deep-water source from the Tethys ocean (Figure 4) due to the closing of the eastern portal of the Tethys Ocean (Hsu and Bernoulli, 1978; Woodruff and Savin, 1989). These results coincide with a global transition in biosiliceous deposition where the pre-MMCO North Atlantic waters rich in biogenic silica migrate into North Pacific and Indian Oceans known as the “silica switch” (Keller and Barron, 1983). The silica switch along with $\delta^{13}C$ comparisons between Pacific and Atlantic oceans are consistent with a strong Tethyan deep-water source,
increased Southern Component Waters, and a high $\delta^{13}$C deep-water source in the North Atlantic. These changes in the oceanic currents are coincident with plate tectonic activity such as the collision of Africa and Eurasia and the Himalayan orogeny.

Figure 4: Paleogeographic images showing the global continent and ocean positioning during the beginning of the Oligocene (above), and beginning of the Miocene (below). Notice the beginning of the Tethys Ocean closure, occurring first at the Eastern edge of the Mediterranean Sea indicated with a red circle restricting global ocean currents to pass between the Laurasian and African continents. Modified images of Ron Blakey at NAU.
The acceleration of polar cooling and EAIS growth could have resulted from pCO$_2$ drawdown as seen through increases in $\delta^{13}$C during the Early-Middle Miocene. The positive $\delta^{13}$C excursion during the MMCO coincides with massive deposits of organic carbon such as the Monterey Formation in California (Vincent and Berger, 1985) and the southeastern U.S. (Compton et al., 1990). The drawdown of atmospheric partial CO$_2$ initiated a positive feedback mechanism and subsequent rapid global cooling after $\sim$14.5 Ma. This theory, termed the “Monterrey Hypothesis,” indicates that the threshold was reached 2-3 m.y. later following the initiation of the MMCO at 17 Ma, and played an important role in the development of the EAIS from 14.5 – 12 Ma. The combination of plate tectonics, changes in deep water ocean circulation, and organic carbon sequestration might all have played a role in the rapid development of the EAIS by restricting equatorial ocean circulation, and aridifying the high-latitude regions. The question remains as to which one had a predominant effect or was the ice-sheet development a result of a combination of these factors?
Chapter 2. Research Hypothesis

As discussed in the introduction, the Middle Miocene Climatic Optimum is classically known to occur from 17 – 14 Ma based on oxygen isotope record from benthic foraminifer (Shackleton et al., 1975; Zachos et al., 2008). The timing of this event is generally accepted, but the causes of this warming event are still debated and a consensus among the scientific community has yet to be reached. The MMCO is marked by two brief yet intense negative $\delta^{18}$O oxygen excursions. In this study, the focus lies within the first phase, from 17-16 Ma. This less than 1 million year event shows a sharp warming episode evidenced by a decrease in $\delta^{18}$O values followed by a prominent increase at 16 Ma, prior to the onset of the second phase of the MMCO. This study intends to investigate the various causes leading to the first phase of the MMCO and quantify how extensive were the effects of this warming period on the environment. To analyze the cause of this event, two main questions are posed. These are:

**R.H. 1) Did the sea-surface temperature rise precede the terrestrial warming associated with the MMCO?**

If sea-surface waters warmed before atmospheric warming occurred, a marine palynomorph signal should show increased abundance and diversity of dinoflagellate cysts and acritarchs prior to increased abundance in fossils of pollen and spore (terrestrial signal). This would imply that the initial warming phase occurred in the oceanic realm as a result of changing ocean currents and increased SST (sea-surface temperatures), with a subsequent impact on atmospheric conditions, hence terrestrial biota. If this is the case, these changes in atmospheric conditions that followed the SST increase could have
induced a spread of vegetation on land, increasing the amount of CO$_2$ removed from the atmosphere because of increased photosynthesis as vegetation spread on nearby land. This resulting reduction in atmospheric CO$_2$ could serve as a negative feedback mechanism (DeConto and Pollard, 2003) that would then decrease the atmospheric temperature, possibly ending the first phase of the MMCO.

**R.H. 2) Was the warming associated with the first phase of the MMCO as intense as the second phase of the MMCO?**

To analyze this, the results of this study are compared with a section in the same core sampled between 350 and 290 mbsf by Warny et al. (2009). To quantify this, the palynological results will be compared to other data such as oxygen isotope data, ice sheet location and depositional environment (lithology). However, such factors could constrain the affects on the high latitude SMS location. For instance, if the warming intensity is matched, freshwater algae is expected to be found within the section along with comparable amounts of *in situ* terrestrial and marine palynomorphs.
Chapter 3. Methods and Materials

3.1 Core Collection and Sample Selection

The 1138 meters of AND2-2A core recovered with a 98% recovery rate were cut and logged on location by the ANDRILL team of scientists, engineers, and workers. The core samples are curated at the Antarctic Marine Geology Research Facility at Florida State University, and core data including images, drilling information, and logs are located on the ANDRILL database accessible on a private FTP website accessible to all members of the ANDRILL SMS science team. The lithology of the core was divided into 14 lithostratigraphic units (LSU) with LSU 1 (1.1,1.2,1.3) and 8 (8.1, 8.2, 8.3, 8.4) divided into subunits (Fielding et al., 2008). The focused section deposited between 460 – 400 mbsf are part of LSU 8.1 (502.69 – 436.18 mbsf) and LSU 7 (436.18 – 339.92 mbsf). The boundary between these two units is at 436.18 mbsf and represents a minor erosional contact with soft sediment deformation where sandy-conglomerates overlie interlaminated siltstones (Fielding et al., 2008). There are distinct correlations between the sedimentology and palynology recovered from the AND2-2A core as discussed later in the study.

The initial preliminary sedimentological and paleontological analysis played a critical role in determining which sections to pursue. Initially, 230 samples were scanned between the depths of 1107 and 200 mbsf interval by the ANDRILL palynology team highlighting a generalized rich section from 460 – 300 mbsf (Taviani et al., 2008). After an initial review of this entire interval, three zones from 460 – 400 mbsf were selected and investigated with higher resolution sampling to determine any relations to the first
phase of the MMCO. They are a diatomite-rich layer deposited between 434 – 431 mbsf that appeared to be the most biologically productive section. And two finer-grained sections sampled between 446 to 438 mbsf and 452 to 450 mbsf. Based on the lithology, these layers could also have reflected warmer climatic conditions and hence provide significant palynomorph assemblages. Table 5 is a list of studied samples. A total of 22 samples were collected between the depths of 455.00 – 403.48 mbsf with the highest sampling concentrations in the biologically rich interval from 435.52 – 430.58 mbsf.

Table 5: Table showing the location of samples around the focused interval. Note the higher resolution sampling from 430.58 – 435.55 mbsf. The asterix indicate samples not spiked with *Lycopodium*.

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</table>
3.2 Age Control

Due to some minor degrees of uncertainty with the age control, the peak conditions of the MMCO in the Ross Sea region could have occurred at any time between 200 – 500 mbsf. The age control adopted for this project is the updated ANDRILL SMS age model provided by Acton et al. (2008) summarized in Figure 6. Age control for the section comes from various sources. Dating methods include magnetostratigraphy, isotope stratigraphy, biostratigraphy (mainly with diatoms), and radiometric dating of volcanic material, which provide an unprecedented high-resolution dating for this Antarctic section. This is fundamental to help constrain the timing of the environmental changes observed in the assemblages. The preferred method of magnetostratigraphy indicates an age of 16.543 Ma at 449.16 mbsf, and 16.268 Ma at 413.26 mbsf (Acton et al., 2008). Diatom analysis at 432 mbsf indicates an age of <17.15 Ma while the diatom assemblage at 312 – 310 mbsf indicates an age range of 15.7 – 15.5 Ma (Taviani et al., 2008). Based on the line of correlation through these various stratigraphic methods (Figure 6), the interval deposited between 460 – 400 mbsf, that is the focused of this thesis, should have been deposited between 16.7 Ma and 16.2 Ma. This age correlates with the initial negative excursion of $\delta^{18}O$ in the Zachos curve (2008) during the onset of the Mid Miocene Climatic Optimum, a phase that is here referred to as the first phase of the MMCO. The three units investigated in this thesis should thus reveal environmental changed that occurred during this first phase.

Assuming uniform deposition rates, the age model indicates that every meter of sediment represents approximately 5,000 years. Hence, the set of 22 samples collected between the depths of 460 – 400 mbsf (Figure 5), with samples taken every ~2.4 meters,
means that there is an average of 12,000 years between sample ages. The highest resolution lies within 435 – 430 mbsf where samples were collected once every meter, giving a higher 5,000-year resolution between samples. Such focused sampling in the core results allows more precision in determining when the events occur and the changes associated with the MMCO.

Figure 6: a) Chronostratigraphic chart for the AND2-2A drill site with stratigraphic log, paleomagnetism, and dating techniques (Acton et al., 2008). The model has absolute dates along the right correlated to regional seismic reflectors (colored lines) and regional thicknesses from DSDP sites. The interval focused on in this study (460 – 400 mbsf) is outlined in red and highlighted in gray. The colors on the stratigraphic log represent: green – diamicrites; gray – mudstones/siltstones; brown – sandstones/conglomerates; orange – volcanics.
3.3 Palynological Processing and Tabulation

In order to study the palynology of a sample, a process of removing unwanted material is required. The isolation of these organic-walled microorganisms involves the removal of siliceous and calcareous materials through acid treatment. Each sample was processed in this manner at Geolab in Alberta, Canada. First, 10-20g samples of core sediments were crushed and treated with hydrochloric and hydrofluoric acids to remove all calcareous and siliceous materials. Samples were then separated using heavy liquid flotation, and the remaining material was sieved between 6 - 250 microns. The remaining residue was mounted on glass slides with glycerin jelly.

Palynomorphs were analyzed using an Olympus BX41 microscope at 60X or 100X magnification under oil immersion for better microscopic definition. Images were captured using a digital Q-Capture camera mounted on the microscope with a 0.5X coupler, images were managed with Qcapture software and plates created using InDesign. For better data control, a systematic form of counting palynomorphs established consistency in results. Each slide was divided into lines, and specimens were counted on each line. Captured images were identified and plotted on a grid for relocation, for example x-y coordinates 15 x 133.

3.4 Data Compilation

The results were tabulated by recording the abundance and diversity of palynomorphs found within each sample at every depth. The total specimens counted per line were computed into the final results allowing for an accurate quantitative assessment of abundance and diversity of species. In order to compare results with those studied
around the 310 mbsf (Warny et al., 2009) interval, two sets of results were used; relative
abundance and concentration in palynomorphs per gram of dry sediment. To estimate
true concentration of palynomorphs, samples were spiked with a known quantity of
*Lycopodium* (club moss spores). The concentration is computed by counting the
recovered *Lycopodium*, and finding the ratio of recovered *Lycopodium*. This ratio was
applied to a palynomorph count to estimate total palynomorphs in the sample. The
estimated palynomorph total is then divided by the sample mass in grams to give a
palynomorphs/gram concentration. Unfortunately, due to a laboratory error, several
samples were not spiked with *Lycopodium* (see asterix in Figure 5). Thus, concentration
data are not available for some of these samples. However, samples were properly spiked
in the rich 435 – 431 mbsf interval, and these concentration results are available for
comparison with the 312 – 310 mbsf interval studied by Warny et al. (2009).
Chapter 4. Results

4.1 Terrestrial Palynomorphs

Terrestrial palynomorphs (e.g., pollen and spores) represent the most abundant palynomorph assemblages recovered within the section of the core analyzed for this study. This is particularly the case in the most biologically-productive zone located between 435 – 430 mbsf. The richest sample at 431.91 recorded exceedingly high concentrations of *Nothofagus* spp. at approximately 2000 specimens per gram of sediment recovered. In the richest samples 434 – 431.91 mbsf, *Nothofagus* spp. comprise over 80% of all terrestrial palynomorphs recovered. Whenever there is a significant amount of terrestrial palynomorphs, *Nothofagus* spp. dominate the assemblages. The spore and conifer assemblages exhibit similar concentrations throughout the 460 – 400 mbsf and throughout the other portions of *in situ* terrestrial palynomorphs. The spore assemblage comprises multiple species of both monolete and trilete spores that are inferred to be *in situ*. The conifer assemblage contains primarily various species of *Podocarpidites* spp. along with a few other undifferentiated gymnosperms. Photographs of key terrestrial palynomorph species are located in appendix (Figures 17-19).

Figure 7 shows a synthesis of the four key groups of terrestrial palynomorphs recovered. The graph on the left shows the distribution of relative abundance in each of these pollen and spore groups in relation to one another. The graph on the right shows the variation in abundances in the studied section for these same four groups, clearly identifying a short zone of high productivity.
Figure 7: Graphs showing the terrestrial palynomorph data. Note that each sample depth on the left does not represent the proper depth scaling between samples. The graph on the left shows the percentage of various palynomorphs with respect to total counts. The graph on the right shows the total count of palynomorphs from each sample. This graph illustrates that 4 samples from 434.01 – 431.91 show >5 times greater the number of terrestrial palynomorphs then the surrounding samples.

4.1.a Pollen Assemblage

The overwhelming majority of the assemblage is dominated by the *Nothofagidites fusca* group. This group is composed of stephanocolpate pollen that belongs to the southern beech family. These *Nothofagidites fusca* pollen types are observed consistently throughout the 460 – 400 mbsf depth range and resemble species commonly found in the Transantarctic Mountains such as those belonging to the Sirius Group studies (Askin and
Markgraf, 1986; Hill and Truswell, 1993), and from Miocene sediments collected from the Cape Roberts Project cores (Raine, 1998; Askin and Raine, 2000; Raine and Askin, 2001). At least two species of Nothofagidites were identified within the studied section, *N. flemengii* and *N. lachlaniae*, with occurrences of possible hybrids of the two species and *N. asperus*, a species adapted to extreme cold environments. The extinct *N. flemengii* is the dominant species recovered throughout the studied section, often outnumbering *N. lachlaniae* by a 5:1 ratio. This said, the distinction between the two becomes difficult at times because many specimen appear to be hybrids of the two species. Regarding the preservation of the fossils, some grains are well preserved but the overwhelming majority are broken, folded over, or faded. This renders the identification between members of the two species difficult. These damaged grains also create challenges in determining whether the grains are in situ or reworked from older sections.

The second most abundant group of terrestrial palynomorphs recovered from the core is composed of various species of conifer pollen. The majority are poorly preserved podocarps that are present throughout the section. A secondary component is composed of various Mesozoic and Paleogene reworked conifer species. A significant number of podocarp sacci are often detached from the grain, but can easily be identified by their distinct ornamentations and shape. The various intact species are differentiated by their ornamentations and the orientation of the sacci with respect to the central body. There are at least two distinct species of *Podocarpidites* that were most abundant within this section of the core. There are a significant number of reworked gymnosperms, which is apparent by their higher thermal maturation, giving the pollen a darker color. Many of these are identified as bisaccate pollen from Mesozoic or Paleogene by their morphology.
and reticulations. For instance, a highly matured specimen of *Alisporites* spp. was recovered at 431.91 mbsf with a distinct dark orange, brown color. The majority of gymnosperm pollen grains occurs within the 434 – 431 mbsf interval and first appear within the studied section at 451 mbsf.

Other species of pollen that contribute to the diversity of the 434 – 431 mbsf section, yet are scattered throughout the 460 – 400 mbsf section, include various angiosperms. These include monosulcates (possibly *Arecipites* sp.), tricolpates, tricolporates (most notably *Tricolporites* sp.), and periporates (either *Periporopollenites* sp. or *Chenopodipollis* sp.). The most common of these pollens are the tricolpate pollen grain *Tricolpites* sp., which most likely represent an *in situ* flora due to their high abundance. *Tricolpites* has been recorded in Middle Miocene sediments in the CRP cores (Raine, 1998), and was determined to be associated with *in situ* deposits from the nearby Transantarctic Mountains. However, the other angiosperm pollen grains present (monosulcates, periporates, and tricolpates) are in low numbers and randomly dispersed throughout section. The good preservation of most of these pollen grains suggests that they might be *in situ*, although some are clearly reworked.

**4.1.b Spore Assemblage**

Even though the *Nothofagidites* and *Podocarpidites* dominate the terrestrial assemblages, there are a variety of spores that occur throughout the section. The spore assemblage consists primarily of bryophytes *Coptospora* sp. and *Rhoipites* sp., with scattered occurrences of other monolette and trilete spores. The two dominant bryophyte species found within this section show similarities to the assemblages found in the Cape Roberts core of Oligocene to early Miocene (Raine, 1998; Askin and Raine, 2000).
These two species are distinguished by the size and ordering of the verrucate patterns where *Coptospora* specimen show coarser verrucate patterns then the *Rhoipites* sp. These monolete spores show affinity to modern liverwort and moss species adapted to cold environments as discussed by Raine (1998) in the CRP cores. Their abundance and preservation in the 434 – 431 mbsf section suggests that these were deposited *in situ*.

While monolete spores represent the majority of spores present, there is a significant amount of trilete spores recovered throughout section peaking at the bio-rich zone. The trilete spores most common throughout section are *Stereisporites* sp. and *Osmundacidites/Baculatisporites* sp. The preservation and age ranges for these spores suggest that these could be *in situ*. The abundance in spores bear similarities to the *Cyathidites* sp. dominated assemblage recorded in Miocene sediments recovered from the Antarctic Peninsula during the NBP03-01A transect (Warny et al., 2006); and the spore assemblage described in the Ross Sea region from CRP-1 core (Raine, 1998). These species represent primitive bryophyte plants well adapted to low temperatures and decreased moisture/precipitation. Figure 8 summarizes the distribution in raw counts of key species throughout the studied interval.

4.1.c Reworked Terrestrial Palynomorphs

Reworking has created many problems throughout this study. This is not surprising when one is studying deposits in Antarctica, a continent that exemplifies reworking by multiple series of advanced and retreat of ice-sheet and associated sediment reworking phase. There is a significant amount of angiosperm, gymnosperm, and bryophyte grains that are possibly reworked and some that were obviously reworked. The latest group was not counted in the graph above.
The first group of “possibly reworked” contains various species of angiosperms that have a range from Paleogene till Pliocene. These were associated with the graph above (Figure 7) because of the strong possibility of being in situ. Many of these species are associated with temperate climates during the Paleocene, Eocene, and Oligocene (Mildenhall, 1989; Askin, 1989) but could have possibly returned during the MMCO. Some of these angiosperm pollen grains present (monosulcates, periporates, triporates, and tricolpates) are in low numbers and randomly dispersed throughout section. Such angiosperms include the triporate *Myricipites harrissii*, periporates *Poropollenites* sp. and *Chenopodiaceae* sp., the monosulcate *Arecipites* sp., and various tricolpates. Many of these pollen grains are well preserved and could represent in situ flora.

The other group contains pollen and spores that are “obviously reworked” because their range is limited to the Late Paleozoic (Permian) and Mesozoic (Triassic–Cretaceous). These specimens are easily identified because they are characterized by a darker color, indicating a very high thermal maturation. These include various trilete spores such as *Dictophylidites mortonii* found at 410.19 mbsf and an older *Stereisporites* sp. at 454.98 mbsf. Along with Mesozoic spores, a single Permian monosaccate likely related to *Cannanoropollis* sp. or *Plicatipollenites* sp. was recovered at 426.98 mbsf. A significant amount of gymnosperms from the Mesozoic were discovered including an *Alisporites* spp. at 431.91 mbsf. As expected, the majority of these reworked Mesozoic species are either bryophytes or gymnosperms as the angiosperms only evolved in the Cretaceous. In some instances, some of the broken or faded gymnosperms recovered within section are difficult to distinguish between Mesozoic and Cenozoic species, and therefore allocated as undifferentiated reworked pollen grains. In general, these
reworked specimens do not occur in the rich interval, but instead are randomly dispersed above and below the 434 – 431 mbsf interval.

Figure 8: Relative abundance of key terrestrial palynomorph groups found within the section of interest. Sample locations are indicated by red bars located left of the lithostratigraphic log. Notice how each assemblage shows peak occurrence at 432.17 and 431.91 mbsf. Note the independent scaling in each column.
4.2 Marine Palynomorphs

The marine palynomorph species recovered have a very low diversity. Only three main species of dinoflagellate cysts, along with a possible dinocyst (*Labyrinthodinium truncatum*) and various forms of acritarch were recovered. Key species of acritarchs include members of the acanthomorph, sphaeromorph, and herkomorph groups. The various dinoflagellates recovered within the section from 460 – 400 mbsf are *Operculodinium centrocarpum*, *Pyxidinopsis braboi*, and *Homotryblum* sp. While the sphaeromorph *Leiosphaeridia* sp. occur most commonly among acritarchs, the occurrence of acanthomorph and herkomorph assemblages are responsible for much of the marine diversity (Figure 9).

The marine palynomorph assemblages exhibit greater abundance and diversity in the intervals deposited above 433 mbsf compared to the older leiosphere dominated assemblage below 435 mbsf. Amongst the rich samples in the 434 – 431 mbsf interval, terrestrial palynomorphs (Figure 7) show higher relative abundance over the marine assemblage (Figure 9). However, marine palynomorphs become more common above 431.91 mbsf then terrestrial pollen and spores. The 431.91 mbsf sample showed *Operculodinium centrocarpum* concentration of approximately 200 specimens per gram of sediment, whereas the *Pyxidinopsis braboi* exhibit a lesser abundance of 50 specimens per gram. The diversity of marine specimen remain primarily constant after the initial increase in diversity found in the bio-rich zone from 434 – 431 mbsf, but overall abundance diminishes up section. Photographs of key marine palynomorphs are located in the appendix (Figures 20 and 21).
Figure 9: Graphs showing the marine palynomorphs data of each sample. Notice that each sample depth on the left does not represent a uniformed scaling between samples. The graph on left shows the percentage of various palynomorphs with respect to total counts. The graph on the right shows the total count of palynomorphs for each sample. Notice how the dinoflagellate numbers increase at the rich section and continue through the younger section.

4.2.a Dinoflagellate Cysts

High concentrations of Operculodinium centrocarpum suddenly occur at 434 mbsf and remain present in samples above 431.91 mbsf, but in smaller concentrations through 403.48 mbsf. The specimens are found primarily as fragments along with numerous pieces of Pyxidinopsis braboi, another dinoflagellate cyst that was found in abundance in the younger section described by Warny et al. (2009). This assemblage is unique to the ANDRILL site as other Antarctic Miocene sediments such as the CRP cores
(Hannah et al., 2000) or the Prydz Bay ODP site 1165 (Hannah, 2005) did not recover abundant specimen *Operculodinium centrocarpum*, and this species is absent in other Antarctic Miocene sections, but none had recovered the MMCO before ANDRILL. The abundance and age range of *Operculodinium centrocarpum* suggest that the specimen recovered are most likely *in situ*. The abundance of fragments most likely indicates breakage that is probably post-depositional. Samples from 434 - 431 mbsf have only a few *Operculodinium centrocarpum* specimens that are fully intact, but they contain numerous fragments. The *Pyxidinopsis braboi* are also mainly present in fragments. It is impossible to know whether they are *in situ* or reworked. They could potentially have originated from the Oligocene where Hannah (2000) noted the abundance of a very similar species (non described) in the Early Oligocene sediments. But several of these specimen were found both intact and broken in abundance in the 310 mbsf interval, so it is quite likely that these are indeed *in situ*, but break easily due to the fragility of their walls.

The sudden appearance of a third species of dinoflagellate, *Homotryblium* sp., at 434 mbsf interval is interesting. The dinoflagellate *Homotryblium* sp. was recovered primarily in the 431.91 mbsf with only several specimens counted. These specimens have a body diameter of 15 to 20 µm with thick, elongated branching processes of 4-8 µm length. The *Homotryblium* species present closely resembles *H. plectilum*, *H. tasmaniense*, and *H. tenuispinosum*, which are species dating from the Eocene and Paleocene. These samples also have other dinoflagellates with similar morphologies yet vary in the types of processes. Other specimens were recorded with processes that branch out less dramatically.
An unidentified marine palynomorph was found at 451 mbsf, yet more abundantly and consistently above the 436.18 erosional contact. This species has a body diameter of 5 to 10 µm with thin, veiled, branching processes of about 4 µm in length. It is very difficult to observe whether an archeopyle is present or not because of the size and preservation of the specimens. If an archeophyle is absent, this would indicate that this species is an acritarch and not a dinoflagellate. Many specimens occur behind pieces of sediment in the slides, and are only partially revealed, making the identification of an archeopyle quite difficult. However, some well-preserved specimens show resemblances to the dinoflagellate *Labyrinthodinium truncatum*. The appearance of *L. truncatum* is first recorded in Northern Mid Latitude regions at 16.5 Ma and last recorded at 7.85 Ma, and the presence of this species at 434 mbsf would represent a first appearance datum of 16.7 Ma in southern high latitudes. The timing of their first appearances and morphological similarities might indicate that these two species are closely related.

4.2.b Acritarch Assemblage

Along with dinoflagellate cysts, significant assemblages of acritarchs were recovered from the 460 – 400 mbsf interval, including specimens belonging to the sphaeromorph, acanthomorph, and herkomorph acritarch groups (Figure 10). The acritarch most abundant within this interval is the sphaeromorph *Leiosphaerida* spp., an unornamented spherical acritarch. These palynomorphs include a broad category of spherical grains with little or no morphological distinctions. Leiospheres represent the most abundant *in situ* marine flora with their highest concentrations at 434 – 431 mbsf, but they also occur consistently throughout the section representing the only other marine palynomorph recovered below 435 mbsf (other than the species similar to *L. truncatum*).
Leiosphere occurrence is recorded in the Mid Miocene sediments of the ODP site 1165 (Hannah, 2005), and the CRP 2-2A core (Hannah et al., 2000). Along with these numerous leiospheres, a significant number of acanthomorph-like acritarchs occur. These are a cross between sphaeromorph and acanthomorphs. They possess a few (5-10) very short spine-like structures (<1 µm) around a small central body that has a diameter of ~15 µm. The morphology of the spines indicates that these are not acanthomorphs, but are probably related to sphaeromorphs. These along with leiospheres comprise the most abundant marine palynomorphs found within section.
Figure 10: Graph showing the distribution of relative abundance in marine palynomorph recovered in the samples between 460 – 400 mbsf. Sample locations are indicated with red boxes. Note the surprising lack of marine flora associated with the finer sediments from 446 – 437 mbsf and also the increase in phytoplankton after the rich interval. Note that scales change between columns.
While the sphaeromorphs represent the largest portion of acritarchs recovered within section, the acanthomorph and herkomorph assemblages remain important indicators for the marine biological diversity during the MMCO. The first acanthomorphs appear at 434 mbsf occurring in significant numbers in all samples between 434 and 431 mbsf. They remain present, but in rare abundances from 430 – 400 mbsf. These specimens are spinulose acritarchs with a body diameter of 10-15 µm and are possibly related to the genus *Micrhystridium*. However, these palynomorphs exhibit a greater number of spines then the traditionally lower number of spines present in *Micrhystridium* (9 – 35) as is discussed in Sarjeant and Stancliffe (1994). Therefore, these specimens might instead belong to the genera *Mecsekia* or *Sigmopollis*. However, due to the absence of an S-shaped aperture and the non-marine nature of *Sigmopollis*, it is most likely that these specimens belong to the genera *Mecsekia*. *Mecsekia* and other small, densely spinulose acritarchs are often misinterpreted as *Micrhystridium*. They are quite ubiquitous and tolerant of a wide range of environments. Examples of their records include Miocene sediments of Nevada (Hedlund, 1965) and Hungary (Hajos, 1966), Oligocene deposits of Japan (Takahashi, 1964), and the Upper Cretaceous of Chile (Takahashi, 1979). They are often labeled as *Micrhystridium* spp.

The final acritarch assemblage studied is the herkomorphs. They represent the acritarch group with the fewest specimen recovered. The herkomorphs have no openings in their wall and have a subpolygonal vesicle divided into fields by crests. Similar to the acanthomorphs, these suddenly appear at 434 mbsf and almost disappear entirely after 431 mbsf. The most common genus recovered is the genus *Cymatosphaera*, which have close affinity to green algae and prasinophytes. The distinguishing characteristic of the
*Cymatiosphaera* specimens present includes a 2-3 µm elevation of the crest from a central body of 20 µm diameter. The specimens show a close affinity to the *Cymatiospheara* species recovered in the CRP cores (Hannah et al., 2000).
Chapter 5. Discussion

5.1 Relationship between Palynological Results and Lithostratigraphy.

The relationship between the sedimentology and biostratigraphy plays an important role in determining the exact boundaries of the Mid Miocene Climatic Optimum within the ANDRILL cores. A debate lies within the contradictory evidence provided between sedimentologists/volcanologists and biostratigraphers on the MMCO boundary. A group of sedimentologists and volcanologists provide evidence of some warming occurring in LSU 11, between the depth of 904.66 and 778.34 mbsf (Fielding et al., 2009). Approximately 125 meters of laminated siltstones and sandstones containing very little diamicritites is found within this section, showing an increase in shells and carbonates (Fielding et al., 2008). To test the hypothesis that there might be problems with the dating, and that the MMCO occurred lower in the core around 900 mbsf, a few of the samples were treated for palynomorphs (Taviani et al., 2008). Warny and her colleagues (Hannah, Raine, and Askin) noted in Taviani et al. (2008) that only rare in situ microfossils were found within LSU 11. They are far less abundant than those found within LSU 8 and 7 (this study). Indeed, the diatom, foraminifera, and palynological evidence presented by the biostratigraphers indicate that the onset of the MMCO most likely occurred around 435 mbsf in the core. These data are in agreement with the synthesis of stratigraphic markers (see the line of correlation in Figure 5).

While only two lithostratigraphic units (LSU 8.1 from 502.69 – 436.18 mbsf and LSU 7 from 436.18 – 339.92 mbsf) were interpreted within the focused interval by the sedimentology research team (Fielding et al., 2008), distinct environmental changes occur within LSU 7 (specifically from 430 – 436 mbsf) as visible in the palynological
assemblages recovered (Figure 11). LSU 8.1 (deposited below 436.18 mbsf) is a mudstone with volcanic clasts, sandstone, and dispersed diamictites (Figure 12). These mudstones exhibit soft sediment deformation and authigenic pyrite, and increased abundance of volcanic clasts within sandstone laminae (Fielding et al., 2008). This unit turned out to be surprisingly poorer in palynomorphs than the fine mud lithology would have expected.

Figure 11: Lithostratigraphic Unit 7 – Images of the transitional interval in LSU-7 overlying LSU-8 at 436.18 – 430 mbsf containing bioclastic rich interbedded sandstones that yielded the highest amounts of palynomorphs. Images a) and b) represent biologically rich sandstones from 433-428 mbsf with high amounts of palynomorphs, macrofossils, and diatoms. c) Clean sandstone from 435 – 434 mbsf with shell fragments and foraminifera.
Figure 12: LSU 8.1 – Interbedded sandy siltstone and mudstones with dispersed clasts below the biologically rich interval 434 – 431 mbsf.  

- a) Interlaminated siltstone 445 – 440 mbsf.  
- b) Silty mudstone 461 – 460 mbsf.  
- c) Diamictites with dispersed clasts within sandy siltstone matrix 439 – 436 mbsf.  
- d) Pumice clasts within interlaminated siltstone 443 mbsf.
Indeed, the two finer-grained sections, a silty mudstone from 446 – 437 mbsf, and a bioclastic rich mudstone at 452 – 449 mbsf, both lithologies that are usually well suited for palynomorph recovery, as they are believed to have been deposited under open-water (ice-free) conditions, were researched with greater resolution to determine any correlation between fine materials and biological activity. Three samples with good recovery at 451.00, 450.00, and 449.46 mbsf showed moderate terrestrial assemblage recovery yet lacked the marine diversity recovered in the rich interval (434-431 mbsf), indicating little correlation between finer grain materials and marine palynomorph assemblages. Samples at 444.98, 442.98, and 439.00 mbsf, also had poor yields in both marine and terrestrial palynomorphs with respect to the richest samples. The results indicate that there is not a simple correlation between these fine grain intervals and increased palynomorph content.

The minor erosional contact with soft sediment deformation at 436.18 indicates that a transition in deposition took place. At that level, a sandy conglomerate overlies interlaminated siltstones of LSU 8.1. Approximately 6 meters of slightly bioturbated, conglomerated sandstone are deposited on top of this erosional surface, between 436.18 and 430 mbsf. These bioturbated sediments indicate that this area was most likely free of ice, that organisms were able to live in this environment, and that the dinoflagellates recovered in that interval are indeed most likely in situ, as we stated by looking at the range and the thermal maturation of the specimens recovered. In terms of lithology, this interval shows little similarities to the volcanic-bearing diamictites that comprises the majority of the lithostratigraphic unit and is indeed reflective of very different environmental conditions. Based on a strict lithological evaluation, the coarser grains interval would not have been assumed to contain more palynomorphs than the underlying
finer-grain sediments. This said, the preserved stratification and abundance of macrofossils (mostly pectenid bivalves with serpulid tubes, bryozoans, and foraminifera) are the highest in this interval, exhibiting a similar increase to what is observed for both marine and terrestrial palynomorphs. The bivalves present in the AND2-2A are similar to the Early Miocene fauna recovered in sites 270 and 272 from DSDP, Leg 28, and represent modern bivalves present in Subantarctic waters near Chile (Dell, 1975). The macrofossil assemblage corroborates that this zone most likely represents an interval with much better environmental conditions, more suitable to life than any other interval recovered by ANDRILL.

This short interval is also characterized by 10-15% biogenic silica comprised of diatoms and sponge spicules. In comparison, the younger rich interval that is correlated to the second phase of the MMCO (the 312–310 mbsf interval described in Warny et al. 2009) exhibited much higher concentrations of diatoms in smear slides (up to 90% biogenic material). Sedimentology and biostratigraphic analysis interpreted multiple sections of diatomite layers in the ANDRILL SMS cores, yet, only the diatomite section at 434 – 430 mbsf (this study) and 312 – 310 mbsf (Warny et al., 2009) exhibits a strong palynological diversity and abundance. Other diatomite layers, such as 451 – 449 mbsf, exhibit weaker palynological signals.

The rest of the sediments overlying the erosional contact at 436.18 mbsf (other than the partial diatomite mentioned above) indicate a change in deposition from siltstone-dominated to a diamicite/sandstone-dominated lithology. These sediments that make up the rest of LSU 7 include 96.26-meter of sediments (Figure 13) marked by increases in sandstones, volcanic debris, and macrofossils (Fielding et al., 2008).
Figure 13: LSU 7 – Series of conglomerated diamictites that dominates the 428 – 400 mbsf interval. Images a) and b) represent larger clasts of granite and volcanic within sandy siltstone matrix. Images c) and d) show brecciated diamictites and sandy conglomerates. Images e) and f) sandy granule dominated and stratified clast rich diamictites.
In summary, the palynomorph assemblages associated with this interval include first upcore appearances of the majority of marine palynomorphs found within the 460 to 400 mbsf section. Many of these species appear at the biorich interval and are sporadically present in the overlying sections. The rest of LSU 7 above 430 mbsf increases in diamicrites and coarser grains indicating ice-rafted debris within a sandstone matrix. This lithological change coincides with decreased palynomorph concentrations yet still exhibit greater abundance and diversity then those recovered below the erosional contact at 436.18 mbsf. Continued occurrence of various marine palynomorphs above the biorich zone reinforces the conclusion that there is not a simple relationship between the presence of finer grain and the abundance in dinoflagellate and acritarch assemblages.

5.2 Comparison of Palynological Results Recovered from the First and the Second Phase of the MMCO.

The results obtained via this research project are compared with results obtained for the youngest part of the MMCO (Warny et al., 2009) where a 2-meter diatomaceous interval (312 – 310 mbsf) proved extremely rich in palynomorphs (see Figure 14). The younger phase of the MMCO was marked by a strong triple palynological signal with sudden increased abundance in 1) marine palynomorphs (dinoflagellate cysts and acritarchs), 2) freshwater algae, and 3) terrestrial palynomorphs (spores and pollen). The dominant palynomorphs recovered were the dinoflagellates *Operculodinium centrocarpum* and *Pyxidinopsis braboi* with a terrestrial palynomorph assemblage dominated by *Nothofagidites* spp., *Podocarpidites* spp., and both monolete and trilete spores (*Coptospora* spp., *Stereisporites* spp., and *Belgisporis* spp.). This overall assemblage shows distinct similarities to the assemblages described in this study, where
we evaluated the first phase of the MMCO. A similar brief, rich interval was tabulated between the depth of 434 and 431 mbsf. The palynological results for the oldest part of the MMCO also show a triple palynological signal with increases in all three types of palynomorphs; terrestrial plants (pollen and spores), marine phytoplankton (dinoflagellates and acritarchs), and freshwater algae (zygospores of Zygnemataceae). But, in this oldest interval, evidence for the freshwater algae Zygnemataceae are very rare; only one was found at 431.91 mbsf, as opposed to about 12 specimens found in samples processed between 312-310 mbsf by Warny et al. (2009). Pollen recovered include similar species as what was found in the 310 mbsf interval, with predominance of genus such as Nothofagidites sp. (primarily N. flemengii and N. lachlaniae), Podocarpidites sp., and various angiosperms such as Tricolpites sp., monosulcates, and periporates, with highest abundance and diversity peaks during an equally very short interval (434 – 431 mbsf). Spores also include species similar to those found in the 310 interval, with some of the most common species being Coptospora sp., and Stereisporites.

The dinoflagellate cysts are also similar to those found in the 310 mbsf interval. The main dinoflagellate cyst species are Operculodinium centrocarpum and Pyxidinopsis braboii, with one exception, Homotryblium sp. is quite abundant in the 434-431 mbsf interval and was not found in the 310 interval. Because fresh water algae are more common in the younger interval, decreasing salinity might account for the Homotryblium community to thrive only in the older section if this species does not tolerate changes in salinity. It would not be surprising that Operculodinium centrocarpum occurred in both section, regardless of the salinity as this species is known to be tolerant of a wide range of sea-surface salinity. Finally, the acritarch species recovered in the 434 and 310
assemblages are also very similar. Key species encountered in the two rich intervals include acanthomorphs (*Impletospheridium* spp. and *Mesekia* sp.), herkomorphs (*Cymatiosphaera* sp.) and sphaeromorphs (leiospheres).

The most significant differences between these two sections lie within the concentrations of marine and terrestrial palynomorphs. When comparing the two biologically rich zones (434-431 mbsf and 312-310 mbsf), it is clear that both exhibit striking similarities in terms of the abrupt abundance increase, and in terms of the types of species recovered. However, the two sections differ in the abundances of the types of palynomorphs recovered. The older 434 mbsf section is dominated by terrestrial species, while the 312 mbsf section is dominated in concentrations by dinoflagellates species. For instance, the much greater algae concentration is visible in some of the two key species present. The concentration of *P. braboi* at 310 mbsf is nearly 2000 specimen per gram of sediment and *O. centrocarpum* show a concentration of 500 palynomorph per gram at the interval (Warny et al., 2009). At 434 mbsf the concentration is difficult to establish due to the broken nature of the two dinoflagellates. However, conservative estimations of dinoflagellate cysts at 431.91 mbsf reveal *P. braboi* concentration of 50 per gram, whereas *O. centrocarpum* show a peak concentration of 200 – 300 per gram. While the marine signal is much weaker at 434 – 431 mbsf, the terrestrial signal recovered is much stronger then the one recovered for the younger warming episode at 310 mbsf. *Nothofagidites* spp. are found in concentrations of up to 70 palynomorphs per gram in the 312-310 mbsf interval (Warny et al., 2009), whereas the concentrations at 431.91 mbsf contain approximately 2000 *Nothofagidites* spp. grains per gram of processed sediment.

The primitive spore assemblage also exhibits much higher concentrations at 431.91 mbsf
then those calculated at 310 mbsf. These two 3–5 meter events both indicate brief warming periods with sparse palynomorph assemblages between the events.

Due to the differences in palynomorph assemblages between the two intervals, there was difficulty in determining which event had a stronger biological signal. The high flux of terrestrially-derived sediments around 432 mbsf might induce a lower dinoflagellate concentrations, when really, it is possible that the presence of these species in surface water was equivalent, but that they were buried under a higher sedimentation rates during the first phase. But if these different concentrations are true reflections of environmental differences (i.e., if terrigeneous input was equivalent), then the diatomaceous layer at 312 – 310 mbsf may represent a time with slightly less vegetation or pollen production, and sea-surface conditions that were more favorable to algal blooms. Because the changes between the two phases are not major, it is difficult to know the true role of sedimentation in the difference between the concentrations found. These intervals could simply represent two similar events only distinguished by the locality of the deposits with respect to where melt-water discharges were centralized. If so, then sediments from 434 – 431 mbsf would show higher concentrations of meltwater deposits allowing a higher terrestrial palynomorph signal. Regardless of mechanisms, the older phase exhibits higher concentrations of terrestrial pollen and spores, while the younger section shows a larger dinoflagellate assemblage.
5.3 What Was the Climate in the SMS Region during the First Phase of the MMCO?

The modern climate of Antarctica is very harsh, and only few plants survive today on the 2% of land that is ice free. Only two types of vascular plants survive on the Antarctic continent today (Smith, 1994) along with lichens, moss, and liverworts. The vascular plants occur mostly on the northernmost edge of the Antarctic Peninsula. In fact, there have been considerable increases in the two vascular plants over the past half-
century primarily through climate change (Fowbert and Smith, 1994). However, in the Dry Valleys, a region to the west of the SMS location, only certain highly adapted lichens survive the harsh conditions (extreme coldness with little to no precipitation) and are only found in protected environments between rocks (Friedmann, 1982). Indeed, the terrestrial biota record has steadily declined throughout the Cenozoic (Warny and Askin, in press; Anderson et al., submitted), and the nature of glacial advances and retreats has redistributed sediments affecting the record of terrestrial life (Reguero et al., 2002). From the Cretaceous-Paleogene, the evolution and rise of angiosperms is well documented in Antarctica (Reguero et al., 2002; Askin, 1990). As temperatures continued to decline through the Neogene, Antarctic sediments from core sampling and outcrop studies provide evidence for plant adaptation to increasingly colder environments. Amidst the declining temperatures of the Cenozoic, the Mid Miocene Climatic Optimum records a final warming event that preceded the glacial conditions seen today, and could hold pivotal clues for future climate changes.

Specifically, the terrestrial biota recovered from this study provides evidence for a marked increase in the vegetative cover between 434 – 431 mbsf in the core, or 16.5 Ma. This increase in vegetation indicates an important climate amelioration that can be correlated to first phase of the MMCO seen in the Cenozoic Oxygen isotope record (Zachos et al., 2008). More details on the climate can be inferred from the types of plants recovered from the assemblage. The in situ pollen and spores are dominated by high abundance/low diversity trends, with a total of ~9 main species (three species of Nothofagidites, two species of podacarps, two monolete spores, and one species of Stereisporites and Tricolpites sp). Due to the high concentrations of these specimens,
and because clusters are known to disintegrate easily with transport, these terrestrial palynomorphs are determined in-situ rather than reworked from older strata. These are indicative of tundra assemblages with sparse, short woody plants and a cover of bryophytes. This sudden deposition of increased vegetation is made of plants that are similar to those found in the Transantarctic mountains east of the SMS site, where the vegetation is known from the Sirius Group outcrops (Askin and Markgraf, 1986; Hill and Truswell, 1993).

It is possible that some limited pockets of vegetation survived the Oligocene and early Miocene cooling, and were able to spread during the MMCO. But some authors suggested that some of the species could also be re-introduced to the Antarctic regions via long-distance transport (Truswell and Drewry, 1984: Smith, 1991). There is one such evidence of long distance aerial transport (Smith, 1991) of South American pollen into the Subantarctic Atlantic areas, yet no mechanism for grain transportation over such distances was provided. Such long-distance transport seems even more unlikely for the Ross Sea regions. Long distant sources would have to come from Tasmania or New Zealand, but modern surface samples such as the CRP-1 lacking miospores has no evidence of such long-distance transport associated with these deposits. However, some of the Miocene West Antarctic islands could be a possible source, yet these pollen grains would require an unlikely journey across the Ross Sea in vast numbers against currents. The glacial activity and history of the McMurdo Sound region suggests that the terrestrial palynomorphs could only derive from the Transantarctic Mountains. The Sirius Group findings in the Transantarctic Mountains of Eary-Mid Miocene outcrops reinforce the source of pollen and spore to in the nearby mountain range (Askin and Markgraf, 1986).
In general, the biological record recovered from the core shows a much more hospitable environment in contrast to modern day Antarctica. The *Nothofagus* and podocarp pollens show evidence of a woody forest habitat that would require a summer temperature of at least 1-2°C. Francis and Hill (1996) conducted an anatomical analysis of the *Nothofagus berdmorensis* wood and leaves from the Sirius Group formation in the Transantarctic Mountains, and their study revealed that these species represented dwarf trees that developed a prostrate habit with short, spreadout branches. This morphological adaptation is likely a response to decreasing temperatures and moisture, which indicates a low, shrubby tundra habitat.

Along with *Nothofagus* specimen, bryophytes are quite abundant (*Coptospora* and *Stereisporites*) in the 434 – 431 mbsf interval. Given the high abundance of these spores recovered during the 434 – 431 mbsf interval, it is very likely that these are indeed *in situ* and represent the low diversity tundra biota. It is interesting to note that bryophyte species require a moist environment to reproduce, hence requiring temperatures above freezing during part of their life cycle. These species were also common in the 310 mbsf assemblage. *Tricolpites* was found in the CRP cores (Raine 1998) and were associated with the *in situ* Miocene flora present. Overall, this bryophyte assemblage is similar to the one described in other Miocene sections such as CIROS-1 cores (Mildenhall, 1989), and the Sirius groups. The constant presence of bryophyte assemblages throughout most of the studied section suggests that these primitive non-vascular plants survived harsh climate fluctuations.
Further supporting the evidence that temperatures had to be above freezing for at least part of the year is the well-preserved specimen of Zygnamatacae zygospore recovered at 431.91 mbsf. This indicates that temperatures were high enough for freshwater pools to accumulate on the surface. The freshwater algae signal is obviously weak at 431 mbsf. It is much weaker then the 310 mbsf signal as only one specimen of Zygnamatacae was discovered and no *Pediastrum*, another common fresh water algae in the 310-mbsf interval, were found. Figure 15 represents the type of environment that must have existed in Antarctica during the two phases of the Mid Miocene Climatic Optimum.

Figure 15: Images of present day analogues showing what the terrestrial environment might have looked like during the Mid Miocene Climatic Optimum in the Western Ross Sea region. The image above shows excellent examples of the bryophytes and plants that would have been found in the region during the MMCO. The image to the right exemplifies the habitat of the *Nothofagus* and represents a maximum warmth environment. However, there are only disputed evidences of grasses flourishing in the Ross Sea region during the Miocene.
Overall, this tundra assemblage with woody plants and bryophytes is an analogue to what is found today in subantarctic South America (Chile and Argentina), Tasmania, and Australia where low clubmoss and other bryophytes cover tundra environments, and occasional short woody beech plants are found flowering during the summer season. These are the principal vegetation of the timberline regions and represent the adaptation of these species to the cooling trend of the Cenozoic.

5.4 Controversy: Sudden Warm Intervals Marking the MMCO or Just Reworked Palynomorphs?

As mentioned earlier, the ANDRILL sedimentologists and volcanologists have provided evidence of some warming occurring in LSU 11, between the depth of 904.66 and 778.34 mbsf (Fielding et al., 2009). Based on their analysis of the lithology, they argued that this 125-m long interval recorded the longest period of ice-free conditions throughout the entire interval and argue that this sequence might have been deposited during the first phase of the MMCO. Some questioned the palynological results and wondered whether or not these palynomorphs could have been reworked. For the reasons listed in the previous sections, these results record mostly in situ palynomorphs and that the two high-productivity peaks (434 and 310 mbsf) recorded the peak of the warmest conditions during the two phases of the MMCO.

Further proof for increased warmth during the Mid Miocene lies in recent evidence compiled from δD values of plant leaf waxes in the AND2-2A core (Feakins, per. comm.). These δD values were measured with respect to Standard Mean Ocean Water (SMOW) and give insight into the H2O cycle. The δD values from plant leaf waxes help determine levels of evapotranspiration and precipitation providing evidence
for the climatic conditions affecting the plant (Feakins and Sessions, 2010; Xie et al., 2000). Dr. Feakins (University of South California) received 10 samples between the depths of 1000 and 300 mbsf where 8 of these samples contained plant leaf wax n-alkanoic acids. She found δD values (SMOW) of ~200 per mil for C\textsubscript{18}, and -180 to -100 per mil for long chain leaf wax compounds (per. comm.). These values were found in the warm interval around 310 mbsf where marine palynomorphs dominated the assemblage. New sampling at 432 mbsf could reveal more evidence of warmth and precipitation.

In comparison, plant leaf wax δD values from the middle Eocene Arctic ranged from -280 to -250 per mil (Jahren et al., 2009), while Arctic δD values through the Paleocene and Eocene ranged from -240 to -150 per mil (Pagani et al., 2006). Modern δD values from snow samples compiled across Antarctica range from -200 to -428 per mil (Masson-Delmotte et al., 2008). A modern study of plant leaf waxes from a desert to coastal environment in southern California indicated δD values from -200 to -100 per mil (Feakins and Sessions, 2010). Therefore, the SMS δD data from plant leaf wax indicates an environment with much higher precipitation and presumably warmer conditions (per. comm.). These data corroborate the evidence from the palynology of the SMS core that the MMCO correlates with the 500 – 200 mbsf section of the core.

**5.5 What Was the Nature of the Coastal Marine Environment in the SMS Region during the First Phase of the MMCO?**

The marine palynomorphs recovered from this study are species that live in the surface waters and hence provide evidence of sea-surface conditions at the time of deposition. Some of the species recovered are typical of those found in some other Miocene Antarctic sediments, but they have never been found in the abundance
recovered from the two rich intervals found in AND2-2A at 434 and 312 mbsf. These two layers show high abundance with low diversity trends similar to the terrestrial data with slightly higher abundance and diversity compared to other Miocene sites recovered in Antarctica thus far. This said, it is important to note than none of the other high-latitude Miocene sites found thus far have sampled the time interval (MMCO) of interest herein.

The abundance in marine palynomorph is found in a very restricted zone. Abundance in phytoplankton was expected in the finer sediments from 451 – 434 mbsf, yet this interval only yielded few dinoflagellate cysts. Leiospheres were the only marine palynomorphs recovered from the 460 – 435 mbsf, along with rare occurrences of *O. centrocarpum* and *L. truncatum*. However, the continuous presence of the sphaeromorph acritarch leiospheres throughout the section implies an ice marginal setting during the Miocene as the leiospheres are mostly abundant today where sea-ice is present part of the year. The study by Mudie (1992) indicates that leiospheres prefer lower temperatures of -2 – 5° C and salinities around 17, in areas where direct input of melting freshwater enters the sea.

The only significant marine palynomorph signal is limited to the interval from 434 – 431 mbsf suggesting a brief southward advance of temperate waters suitable for dinoflagellates and phytoplankton. Marine palynomorphs continued to occur from 431 – 400 mbsf, but in much less abundance then the peak interval below implying that the SMS location quickly reverted to less tolerable conditions. In order to understand this brief period of intense biological activity, the assemblage must be studied from an ecological standpoint for the various types of palynomorphs recovered.
The brief presence of *Homotryblium* sp. indicates one of two possibilities: *Homotryblium* sp. grains are reworked from Paleogene sediments and that reworking has a much greater effect on the marine assemblages than previously understood. The other possibility is that this particular species reappeared in Antarctic waters, and could indicate an improvement in marine conditions that is associated with the Mid Miocene Climatic Optimum. The *Homotryblium* sp. occurrence along with the morphologically similar *L. truncatum* species suggests that these are reappearances of species similarly adapted to a high terrestrial input environment. *L. truncatum* is recorded throughout the MMCO in other studies (Piasecki, 1980, and Piasecki, 2002) as a dominant dinoflagellate cyst. However, these studies are located in mid–high latitudes of the northern hemisphere.

Based on comparison of these results with the rest of the ANDRILL core (Taviani et al., 2008), it appears that the relatively (for the Miocene of Antarctica) abundant dinoflagellate assemblage found at 434 mbsf represents a significant time when climatic conditions improved at the AND2-2A core location. While leiospheres and *Cymatiosphaera* are present in other Antarctic Miocene sediments such as the CRP cores (Hannah et al, 2000), and the ODP site 1165 (Hannah, 2005), the dinoflagellate assemblage along with the acritarch *Mecsekia* remains unique to the region. *Operculodinium centrocarpum* are not present in the Miocene sediments of the other Antarctic sections listed above, yet both contain the dinoflagellate *Lejeunecysta* as dominant species. In the CRP cores, the sediments are early Miocene and the middle Miocene section is absent where Pliocene sediments unconformably overlie early Miocene. The CRP location is ~90 km northeast of the SMS location and represents a
similar setting during Miocene. *Lejeunacysta* presence in Early and Middle Miocene sediments of ODP 1165 and CRP represents the southward extent of this species during the Miocene. *Lejeunacysta* are also present in Late Miocene - Pliocene sediments from the NBP03-01A transect in the Northern Basin of the Ross Sea (Warny et al., 2006) showing that this species survived through the Miocene into Pliocene. The absence of *Lejeunacysta* and overwhelming abundance of *O. centrocarpum* suggests a transition in marine environment that is favored by *O. centrocarpum*.

The *O. centrocarpum* grains are mostly present as fragments, which would initially suggest reworking. However, the high concentrations of these specimens with several grains still intact imply that these dinoflagellates were deposited *in situ*. The fragmentation of these dinoflagellates must have resulted from a tumultuous depositional environment. This is also evident in not only the terrestrial palynomorphs (particularly *Nothofagus* and bissacate pollen specimen), but also through sedimentology and the other marine species present. While only pieces of *P. braboi* are found from 434–430 and occur sparingly from 431–400 mbsf, greater concentrations are recorded by Warny et al. (2009) from 312–310 mbsf, and the species found at that level are most commonly intact.

The appearance of *Mecsekia* sp within the rich section provides further evidence for the highly productive period. The biological affinity of these small spinulose acritarchs is disputed, but their occurrences are noted in coarser grained sediments in the AND2-2A core and in other samples in Egypt (Schrank, 2003), Japan (Takahashi, 1964), and Chile (Takahashi, 1979) often labeled as *Micrhystridium* spp., while dinoflagellates dominate finer grained sediment. This could suggest that these small acritarchs survived interstitially between sand grains in more agitated waters, as noted through their
occurrences in phosphoritic sandstones throughout the Paleogene and Neogene (Schrank, 2003). However, small size in acritarchs traditionally is attributed to adaptation to a planktonic lifestyle, which is contradictory to an interstitial mode of life in sediments. Regardless, such sedimentary environments appear best suited for small acritarchs to attain higher diversities and abundances. The sediments above the 436.18 mbsf erosional contact contain high-energy sandstone deposits more suitable for these small acritarchs to flourish over dinoflagellates, yet transitions into sandy diamictites where their numbers suddenly decreased sharply and dinoflagellates continued to occur in lesser numbers. This suggests a change in temperature in the marine realm and could coincide with changes in alkalinity and salinity once the temperatures dropped between phases of the MMCO.

In summary, the dinoflagellate and acritarch assemblages are indicative of an environment with presence of sea-ice during part of the year, but with presence of ice-free areas that allowed for periods of brief but important algae blooms, with two major intervals of warmer climate and sea-surface waters, as evidenced by the fossil record from 434-431 and 312-310 mbsf. The presence of *Zygnemataceae* supports the theory that freshwater input from the Transantarctic Mountains reached the SMS region and played a role in controlling sea-surface salinities and thus marine biodiversity. Marine surface conditions must have been warmer in the younger 312-310 mbsf interval because that interval exhibited a stronger freshwater algae signal that also coincided with greater concentrations of dinoflagellate cysts than those recovered at 434 – 431 mbsf.
5.6 Implications for the Mid Miocene Climatic Optimum

Based on the age model provided by Acton et al. (2008), the two high-productivity (in both pollen and phytoplankton) intervals represent the warming event associated with the two phases of the MMCO. The section studied provided evidence for a much warmer Antarctic region during the first phase of the Mid Miocene Climatic Optimum then previously recorded as seen through marine and terrestrial palynomorph assemblages. Specifically, the implications for this study revealed a prominent warming event that is recorded in the Ross Sea region during the Mid Miocene Climatic Optimum.

Due to excellent dating from various sources, the brief warming interval at 434 – 431 mbsf is accurately dated to the first phase of the MMCO between 16.7 – 16.2 Ma. These dates correlate well with δ18O records from benthic foraminifera indicating that the peak warming for the first phase of the MMCO lies at 16.5 Ma. Terrestrial data revealed that the local climatic conditions were far warmer and allowed for a prominent return of plant life to the Ross Sea region during a brief interval of time that corresponds to only 4 meters (possibly a time as short as 20,000 years). The event also represented a localized peak in abundance and diversity of marine palynomorphs that suggested the climate and marine conditions improved simultaneously.

However, the terrestrial signal was far stronger then the marine signal recorded at the rich interval from 434 – 431 mbsf (Figure 16). But this might be an artifact linked to sedimentary conditions. The terrestrial signal showed similarities in each peak intervals, except for one difference; the first phase is dominated by terrestrial assemblages at 434 mbsf, while the second phase is dominated by marine assemblages at the younger 310
mbsf. But again, these changes in concentrations could result from changes in deposition flux. If so, the dominant terrestrial input might have simply overshadowed the localized marine productivity, thus effecting the marine concentrations of the various dinoflagellates recovered.

Figure 16 – Graph showing the ratio between terrestrial and marine palynomorphs on a logarithmic scale next to a summary of abundance figure. Note the biorich interval highlighted in green while the poor recovery zones are highlighted in red.
Chapter 6. Conclusions

The palynological assemblages recovered in this study revealed an extraordinary pulse of biological activity on land, accompanied by an important increase in dinoflagellate and acritarch diversity in the surface waters. This indicates a significant amelioration of climatic conditions both on land and in the western Ross Sea during part of the studied time interval. The data indicated that this event occurred during a short 4-m interval recorded in the ANDRILL SMS core between the depths of 434 to 431 mbsf. This event was similar in intensity and abruptness to the only one other rich palynological interval in the core, located between the depths of 312-310 mbsf. Correlation of this 4-m interval to the ANDRILL age model allowed accurate dating within this interval of warmth to be of middle Miocene age, most likely at 16.5 Ma. This specific time interval correlated with the first significant increase in temperature known as the first phase of the Mid Miocene Climatic Optimum, according to the Zachos et al. (2008) oxygen isotope data.

Using an average sedimentation rate for the core, the warm interval associated with the first phase of the MMCO could have lasted as little as 20,000 years, and possibly less if the sedimentation rate were much higher during this time interval as it was most likely free of sea ice and hence might have received higher sediment input. This timing of the phase represents the height of the first phase of MMCO warming and the high latitude region of SMS records only the maximum global effects of the event. The concentration in plant pollen and spores recovered from this study is much greater than that recovered from the rich assemblages found in the 312-310 mbsf section that was linked to the second phase of the MMCO. On the other end, the studied section revealed
a far weaker dinoflagellate cyst assemblage. This could indicate that the first phase of climate warming was stronger on land than during the second phase, but the differences in palynomorph assemblages could be linked to sedimentological factors where the first event experienced increased terrigeneous input (hence more pollen, and diluted phytoplankton). Thus, the data does not determine with certainty whether any of the two phases of the MMCO was characterized by greater warming.

Despite the first event being dominated by pollen and spores, data on sediment flux would be needed to establish if the first phase of the MMCO was truly climate driven as opposed to induced by sea-surface warming driven by changes in ocean currents. Despite lower concentrations of marine versus terrestrial palynomorphs, the sudden increase in abundance in dinoflagellates and acritarchs suggest a rapid change in the oceans surrounding Antarctica during the onset of the Mid Miocene Climatic Optimum and persisting throughout the event. The greater concentration of phytoplankton found within the second phase of the MMCO is possibly the result of more stable favorable marine conditions.

One possible cause for the ending of the Mid Miocene Climatic Optimum could be found in a negative feedback mechanism. Indeed, the data revealed that the Antarctic region during the Miocene contained a much greater concentration of plant biological activity then previously understood. Vegetation probably flourished at the favor of a globally warmer climate during the MMCO. The spread of vegetation on land meant an increasing amount of CO\textsubscript{2} being extracted from the atmosphere as a result of increased photosynthesis activity. This reduction in atmospheric CO\textsubscript{2} might have been sufficiently important to induce a negative feedback mechanism that would have decrease the
atmospheric temperature to a point where the newly-established, fragile, warmer habitat was no longer hospitable for plants. This negative feedback mechanism, along with other key factors such as oceanographic changes and tectonics, possibly played a role in ending the Mid Miocene Climatic Optimum.
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Appendix: Images of Palynomorphs

Figure 17 – Plate #1: Selected terrestrial palynomorphs from AND-2A. Scale bar = 20µm
Figure 18: Selected spore from AND-2A. Scale bar = 20 µm
Figure 19: Various angiosperm pollen grains recovered. Scale bar = 20 µm
1) Poropellenites sp., 2-3) Chenopodiaceae spp. 4) Tricolpites sp, 5) Arecipites sp 6) Osmundacidite/Baculatisporites complex, 7-9) various tricolporates, 10) Myricipites harrissii, 11) unidentified tricolpate
Figure 20: Selected marine palynomorphs. Scale bar = 20 µm
1) Operculodinium centrocarpum, 310 mbsf  
2) & 3) O. centrocarpum fragments, 431 mbsf  
4) Pyxidinopsis braboi, 310 mbsf  
5) P. braboi, 431 mbsf  
6) P. braboi, 434 mbsf  
7) Homotryblium sp, 431 mbsf  
8) Homotryblium sp?, 434 mbsf  
9) Homotryblium sp?, 431 mbsf  
10) Labyrinthodinium truncatum?, 426 mbsf  
11) L. truncatum?, 414 mbsf  
12) L. truncatum?, 451 mbsf
Figure 21: Selected palynomorphs from AND-2A. Scale bar = 20 µm
Vita

Lee Ryan Foersterling was born in Baton Rouge, Louisiana, and spent most of his childhood in Mandeville, Louisiana. After graduation from Mandeville High School in 2003, he attended Louisiana State University. Upon completion of his Bachelor of Science in Geology, he tested the job market for a semester before returning to LSU to pursue a Master of Science in geology. He plans to work for an oil/gas company after completing his M.S.