A Palynological Analysis of Seymour Island and King George Island off the Antarctic Peninsula: A Dating and Climatic Reconstruction

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A PALYNOLOGICAL ANALYSIS OF SEYMOUR ISLAND AND KING GEORGE ISLAND OFF THE ANTARCTIC PENINSULA: A DATING AND CLIMATIC RECONSTRUCTION

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in

The Department of Geology and Geophysics

by Caven Madison Kymes B.S., Louisiana State University, 2013 December 2015
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ABSTRACT

During the Cretaceous and early Paleocene, Antarctica was covered by lush vegetation. However, Antarctica today is covered with ice and snow leaving less than 1% of the continent inhabited by vegetation. By studying this decline in vegetation and reconstructing past environments, we can gain a better understanding of environmental changes and use this knowledge to predict future changes.

In this thesis, I present my results and interpretations of palynological changes across the Antarctic Peninsula during the Late Eocene, Middle Oligocene, and Miocene. The first study discusses a paleoenvironmental reconstruction of the upper La Meseta formation (Late Eocene), Seymour Island, and Polonez Cove formation (Middle Oligocene), King George Island. My results indicate a relatively decent abundance of *in situ* podocarp conifers and southern beech *Nothofagidites* (*brassii*, *fusca*, and *menziesii* gp.) palynomorphs present within the lower section of the studied La Meseta Formation. This implies the area was relatively free of ice and sparsely inhabited with a temperate-like forest in the Late Eocene. Progressing up section, the presence of sea-ice indicative acritarchs called *Leiosphaeridia* spp. and the dominance of cool-loving *Nothofagidites* sp. (*fusca* gp.) indicate a climate cooling as the region became more glaciated. Evidence of this cooling is more apparent based on the majority of palynomorphs which appear broken and the samples being dominated with *Leiosphaeridia* spp. in the upper most studied section of La Meseta formation and through the entire section of the Polonez Cove formation. Lastly, my second study discusses a palynological interpretation of Miocene samples collected from the Cape Melville formation on King George Island. The samples revealed a near-shore depositional environment dominated by sea-ice as indicated from the abundance of leiospheres. These samples are also dominated by various reworked palynomorphs of Permian to Paleogene.
age, mixed with rare *in situ* Miocene specimens. This study provides new insight into the provenance of the reworked assemblage and give new information on probable glacial advances.
CHAPTER 1: INTRODUCTION TO ANTARCTIC EARTH SCIENCE

1.1 Thesis style

This thesis is presented in the style of stand-alone articles that have been published or are in preparation for publication in multiple scientific journals at the time of defense. This article discusses a palynological analyses of samples collected from two islands located off the Antarctic Peninsula. Chapter 2 discusses a paleoenvironmental reconstruction using palynomorphs observed in samples collected from the upper section of the La Meseta Formation, Seymour Island, and Polonez Cove Formation, King George Island. Chapter 3 examines palynomorphs observed in samples collected from the Cape Melville Formation, King George Island, to determine the paleoenvironment present during the Miocene as well as to identify possible provenances for reworked palynomorphs witnessed throughout the section. Chapters 2 is preceded with a brief introduction of Antarctic paleoclimates since the Tertiary and is followed with a broad conclusion.

1.2 Brief overview of projects and materials studied

In order to better understand climate change in Antarctica over the last ~36 Ma, I analyzed palynological assemblages (e.g. pollen, spores, and marine dinoflagellate cysts) in samples collected from three outcrops, spanning three geologic epochs, on two islands off the Antarctic Peninsula. (1) Palynological assemblages were observed in fourteen samples collected from the La Meseta Formation, Seymour Island, to better date the formation and understand the vegetation’s response prior to the Eocene-Oligocene Transition (EOT). (2) Analyzed palynomorphs were observed in sixteen samples collected from the Polonez Cove Formation, King George Island, to understand the vegetation’s response after the climate shift into the cooler Oligocene epoch. (3)
Finally, observed palynomorphs in twelve samples collected from the Cape Melville Formation, King George Island, were analyzed to determine the vegetation’s response to further cooling in the Miocene epoch, as well as, to identify possible provenances for glacial migration.

The two research projects discussed in this thesis focus on two islands located off the Antarctic Peninsula: (1) Seymour Island, part of the James Ross Island Group, and (2) King George Island, the largest island of the South Shetland Island Group (Figure 1.1).

Figure 1.1. Satellite image of Antarctica with key geographic locations. Site locations located off the Antarctic Peninsula highlight Seymour Island and King George Island.
1.3 Antarctic Cenozoic history

By the early Ordovician, the landmasses comprising the supercontinent known as Gondwana had assembled. The large landmass remained intact until the continents began to separate during the Permian due to intrusion and extrusion of mantle-derived magmas (Anderson, 1999). During the Middle Jurassic, large normal faulting engendered rift systems which separated East Gondwana from West Gondwana (de Wit et al., 1998). Separation of Antarctica from Gondwana continued into the Late Cretaceous (~72 Ma) where West Antarctica diverged from New Zealand and settled to its current isolated location (Stock and Molnar; 1987).

While Antarctica was part of Gondwana, the climate was warm and the continent was lush with vegetation. However, once Antarctica was completely separated from Gondwana, the climate began to cool sometime around the Eocene-Oligocene boundary (~34 Ma) and vegetation began to deteriorate (e.g. Birkenmajer and Zastawniak, 1986; Anderson et al., 2011). This decline in vegetation continued through the Oligocene where the majority of the vegetation was comprised mostly of the cool loving Nothofagidites fusca group and rare Podocarpidites sp. (e.g. Warny and Askin, 2011b; Warny & Kymes, 2013). Cooling of the Antarctic Peninsula continued into the Miocene where vegetation was minimal and glaciation became very prominent, covering most of the region.
2.1 Abstract

The Eocene-Oligocene Transition (c. 34 Ma) is a time when Earth’s climate shifted from a relatively ice-free world to one with glacial conditions spreading to many regions of Antarctica. This climatic transition has been studied from various proxies including oxygen isotope ($\delta^{18}O$) values and atmospheric carbon dioxide accumulation rates. This paper focuses on changes in vegetation (pollen and spores) and marine algae (dinoflagellate cysts) around this important transition thanks to a palynological analysis of 30 samples collected from two islands (Seymour Island and King George Island) located west of the Antarctic Peninsula. Our results indicate that conditions in the Peninsula were cool in the latest Eocene. Terrestrial vegetation was low diversity and dominated by Nothofagus of the cool-cold climate fusca group, and the marine organic-walled phytoplankton was reduced to mostly leiospheres and rare species of dinoflagellate cysts such as Vozzhennikovia rotunda, V. apertura, Senegalinium asymmetricum, and Spinidinium macmurodense. This latest Eocene vegetation, similar to Valdivian-type forest found in modern day Chile and Argentina, was drastically reduced by the mid to late Oligocene, as very few in situ palynomorphs were observed in the Oligocene samples analyzed. By mid-Oligocene, the algal content is almost entirely comprised of the sea-ice indicative leiospheres, confirming that cooler climate and sea-ice was present in the Peninsula, and this northernmost region of Antarctica was already trending towards modern polar climatic conditions.
2.2 Introduction

The Eocene-Oligocene Transition (EOT) (ca. 34 Ma) denotes a global cooling event marked by substantial ice growth in Antarctica and high latitude sea-surface temperature changes from ~18°C during the beginning of the Eocene to ~6°C transitioning into the Oligocene (Stott et al., 1990; Liu et al, 2009). This ice growth ensued as temperatures changed from the “greenhouse” conditions of the Early Cenozoic to the present day glacial state (Prothero et al., 2003; Lear et al., 2008). This ~12°C temperature change has been correlated with an increase in deep-sea benthic foraminiferal oxygen isotope (δ¹⁸O) values, as well as records of atmospheric carbon dioxide concentrations (Zachos et al., 1996; Prothero and Berggren, 2014). Although several recent studies have been conducted on this transition based on sediments cored off the Antarctic Peninsula by the SHALDRIL program (Anderson et al., 2011; Griener et al., 2013; Feakins et al., 2014), only a few studies have focused on the analysis of the Eocene/Oligocene continental climate evolution, mainly because of a dearth of exposed sediments or core samples of this age on the Antarctic continent.

Here we revisited one of the best studied Eocene sections by focusing on the uppermost portion of La Meseta Formation on Seymour Island, and compared the Eocene assemblage we recovered with that of a less studied Oligocene section; the Polonez Cove Formation on King George Island. A total of thirty (30) samples were analyzed for palynology; 14 collected from La Meseta Formation on Seymour Island and 16 from the Polonez Cove Formation on King George Island (Figure 2.1), both sites are adjacent to the Antarctic Peninsula. These islands provide a rare opportunity to study Eocene/Oligocene outcrops as they are part of a handful of locations in Antarctica where ice cover is minimal, allowing us to access sections of this age without international drilling efforts.
2.3 Geologic Setting

Seymour Island is located approximately 100 km to the southeast of the Antarctic Peninsula (Figure 1B) at 64°17’S latitude and 56°45’W longitude. The island is roughly 20.5 km long, 9.6 km wide, and reaches 200 m above sea level at the highest point (Elliot et al., 1975). Seymour Island outcrops are well exposed, due to the lack of permanent ice, making it an ideal location for this study. The geology of the island is subdivided into four formations known as the Lopez de Bertodano (upper Campanian-lower Danian), Sobral (Danian), Cross Valley (Late Paleocene), and La Meseta (Eocene) (Elliot and Trautman, 1982; Rinaldi et al., 1978; Marenssi et al., 1998a) (Figure 2.2).
Figure 2.2. Geologic map of Seymour Island modified from Sadler (1988) highlighting the four major formations. The samples collected from La Meseta Formation are represented by the D6 transect line. The star next to the stratigraphic column marks the location of the samples. Legend: Grey- recent fluviglacial deposits, Yellow- La Meseta Formation (Eocene), Light yellow- Cross Valley Formation (Early late Paleocene), Light tan- Sobral Formation, unit 4 (Early Paleocene), Orange- Sobral Formation, unit 3 (Early Paleocene), Tan- Sobral Formation unit 2 (Early Paleocene), Brown- Sobral Formation, unit 1 (Early Paleocene), Light green- Lopez de Bertodano Formation, unit 10 (Late Maastrichtian-Early Paleocene), Dark green- Lopez de Bertodano Formation, units 1 - 9.
Seymour Island, and the surrounding James Ross Island group, developed as part of a back-arc basin in the Antarctic Peninsula area, when the Phoenix Plate (Pacific lithosphere) subducted beneath the Peninsula (Barker 1982; Macdonald et al., 1988; Guterch et al. 1985). The back-arc basin experienced oblique extension along the easternmost margin, which controlled the development of the surrounding sedimentary basins (Storey and Nell, 1988). This basin infill is categorized as a mega-regressive clastic sequence measuring between 6 and 7 km thick and dating from Barremian to Eocene in age (Macdonald et al., 1988). Volcanism in the area was sporadic and lasted from Jurassic to possibly Eocene. During this time, tilting of synsedimentary strata was congruently intermittent with the volcanism. This succession is in exposed sections of Seymour Island (Macellari, 1988; Rieske, 1990).

Deposition of Seymour Island strata occurred as sediment was proximally supplied by an active magmatic arc from Cretaceous to Paleocene (Lopez de Bertodano Formation). Distal sediment accumulated through Eocene times (Hoffman et al., 1991; Macellari, 1992; Marenssi et al., 1999). During the Danian age, around the time deposition of the Sobral Formation occurred, the magmatic arc was dissected; exposing metamorphic and plutonic rocks. The Late Paleocene’s Cross Valley Formation, on the other hand, experienced periodic volcanic activity, resulting in a rejuvenated volcanic source area (Hoffman et al., 1991).

The unconsolidated samples collected from the uppermost sandstones of La Meseta Formation are the focus of the Late Eocene portion of this climatic study. This formation was deposited as a mix of deltaic, estuarine, and shallow marine setting (Marenssi et al., 1998a,b).

King George Island (KGI) is the second island sampled for this study. KGI is located approximately 120 km off the northern coast of the Peninsula and lies at 62°01’S latitude and 58°33’W longitude (Figure 2.1B). KGI is roughly 95 km long and 25 km wide; making it the
largest island of the South Shetland Islands (SSI). The island itself is detached from the Peninsula by a young back-arc rift structure, the Bransfield Strait (Figure 2.1B), which spans 500 km along the Pacific margin (Galindo-Zaldívar et al., 2004). This arc was also developed as the Phoenix Plate (Pacific lithosphere) subducted beneath the continental crust of the Antarctic Peninsula, much like the James Ross Island Group (Barker, 1982; Guterch et al., 1985). The geology of KGI consists mostly of Mesozoic and Cenozoic eruptives and associated pyroclastics, which are cut by hypabyssal and abyssal intrusions (Smellie et al., 1984; Haase et al., 2012). The majority of these eruptives and pyroclastics are a result of high volcanic activity, which took place during the Eocene (Wang et al., 2009; Nawrocki et al., 2011). However, volcanism abated as the transition from the Eocene to the Oligocene occurred, coinciding with a northward progradation of the Antarctic ice sheet and marine transgression (Baker, 2007).

KGI is comprised of three stratigraphic sequences consisting of the Upper Cretaceous through Oligocene and Lower Miocene (Birkenmajer, 1990, 2001). These sequences are divided into three main groups: Chopin Ridge Group, Moby Dick Group, and the Legru Bay Group. The Chopin Ridge Group consists mostly of marine tillites, porphyritic lava flows, and sandstones, which make up the three formations of the Chopin Ridge Group (Birkenmajer, 1987). Of the three formations, the Polonez Cove Formation serves as the focus of KGI and the portion of this paper in which we discuss the environment present during the Oligocene (Figure 2.3).
2.4 Studied materials

Fourteen samples from La Meseta Formation and sixteen samples from the Polonez Cove Formation were analyzed. All fourteen latest Eocene (?earliest Oligocene) samples were collected from the uppermost La Meseta Formation. These samples were collected for Dr. Rosemary Askin in 1984 and were obtained for this study from the Polar Rock Repository (PRR) at Ohio State University. The sixteen mid to late Oligocene samples analyzed for this study come from a suite of exposed sections of the Polonez Cove Formation (see Fig. 2.4 for details). However, the majority of the samples were collected from the Linton Knoll profile (Figure 2.5). All samples analyzed from the Linton Knoll profile were collected by the Polish Academy of Science (PAS) two-part expedition, which took place in January 2007 and January 2009.
2.5 Methods

Samples were processed using standard chemical palynological processing techniques. Dry sediment was weighed and spiked with a known quantity of *Lycopodium* spores to allow for calculation of palynomorph concentrations. Dry sediment was successively treated with hydrochloric acid, hydrofluoric acid, and heavy liquid separation (e.g. Brown, 2008). Samples were sieved between a 10 and 250 μm fraction, and the remaining residue was mounted on microscope slides using glycerin jelly.

Palynomorph counting was conducted in the Louisiana State University’s Center for Excellence in Palynology (CENEX) lab. When possible, 300 palynomorphs were tabulated per sample using an Olympus BX41 microscope. Palynomorphs were identified to the lowest taxonomic level possible. After palynomorphs were tallied, palynomorph concentration was calculated for each specimen using the equation from Benninghoff (1962): \( C = \frac{P_c \times L_t \times T}{L_c \times W} \), where \( C \) = concentration (per gram of dried sediment, gdw\(^{-1}\)), \( P_c \) = the number of palynomorphs counted, \( L_t \) = the number of *Lycopodium* spores per tablet, \( T \) = the total number of *Lycopodium* tablets added per sample, \( L_c \) = the number of *Lycopodium* spores counted, \( W \) = the weight of dried sediment.

2.6 Results

2.6.1 Palynological results from the La Meseta Formation

The fourteen La Meseta samples studied yielded well-preserved palynomorphs, but with a relatively low diversity (Plates 1-6 see appendix B). The majority of palynomorphs identified in the oldest part of the studied section (D6-01 through D6-07) are *in situ* (~42% *in situ*), but the
assemblage progressively becomes more reworked (~40% reworked) (excluding the leiospheres) in the upper portion of the outcrop (D6-08 through D6-14). Reworked species of palynomorphs range from Permian to Paleocene in age and have been well documented on Seymour Island and the islands surrounding the Antarctic Peninsula (eg. Askin & Elliot, 1982; Askin, 1983, 1988, 1990; Dettmann & Thomson, 1987; Riding & Crame, 2002; Bowman et al., 2012). Age-significant dinoflagellate species were corroborated with age ranges from Ocean Drilling Program’s (ODP) publication 189 (Sluijs et al., 2003). The presence of Vozzhennikovia rotunda (Lentin and Williams, 1981), V. apertura (Lentin and Williams, 1981), Senegalinium asymmetricum (Stover and Evitt, 1978), and Spinidinium macmurodense (Wilson, 1967) indicates that the uppermost section studied is Eocene in age. The concentrations in palynomorphs ranged from 119 to 987 per gram of dried sediments (Table 2.1), which overlaps the Eocene concentrations of 500 and 18,000 recovered palynomorphs from the Eocene section sampled by the SHALDRIL program off the Antarctic Peninsula (Warny and Askin, 2011a). The following information provides an overview of the species found per sample, from the oldest to the youngest sample. All fourteen samples were collected from the Telm6 (1 sample) and Telm7 (13 samples) section of La Meseta Formation. The Telm6 section is composed of unconsolidated green and purple sand. The Telm7 section is composed of mostly unconsolidated green and purple sand with intermittent shells dispersed throughout (Sadler, 1988).
Table 2.1. Palynomorph concentration for the uppermost Eocene section (Telm6 and Telm7) of the La Meseta Formation.

<table>
<thead>
<tr>
<th>La Meseta Formation Samples and Palynological Concentrations</th>
</tr>
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<tbody>
<tr>
<td>Sample name</td>
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<tr>
<td>--------------</td>
</tr>
<tr>
<td>D6-14</td>
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<td>D6-13</td>
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<td>D6-12</td>
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<td>D6-11</td>
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<td>D6-10</td>
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<td>D6-02</td>
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<tr>
<td>D6-01</td>
</tr>
</tbody>
</table>

La Meseta: sample D6-01 (0 m), Telm6

The sample yielded a majority of reworked palynomorphs comprising *Cyathidites minor*, *Dictyophyllidites* ssp., *Laevigatosporites ovatus*, *Leiotriletes directus*, *Podocarpidites* sp., *Punctatisporites* sp., *Triporopollenites* sp. *In situ* species included *Leiosphaeridia* ssp., *Myricipites harrisii*, *Nothofagidites* sp. (*brassii* gp.), *Nothofagidites* sp. (*fusca* gp.), *Nothofagidites* sp. (*menziesii* gp.), *Phyllocladidites* ssp., *Proteacidites* cf. *p. parvus*, *Vozzhennikovia rotunda*

La Meseta: sample D6-02 (3 m), Telm7

The sample yielded a majority of reworked palynomorphs comprising *Alisporites* sp., *Clavifera triplex*, *Dictyophyllidites* sp., *Osmundacidites wellmannii*, *Podocarpidites* sp., *Proteacidites* sp., *Triporopollenites* sp. *In situ* species included *Cyathidites minor*, *Leiosphaeridia*
spp., *Myricipites harrisii*, *Nothofagidites* sp. (*brassii* gp.), *Nothofagidites* sp. (*fusca* gp.), *Nothofagidites* sp. (*menziesii* gp.), *Senegalinium asymmetricum*, *Spinidinium macmurdoense*, *Vozzhennikovia rotunda*. This sample showed a dramatic increase of *Podocarpidites* species compared to that of the D6-01 sample.

**La Meseta: sample D6-03 (6 m), Telm7**

The sample yielded a majority of reworked palynomorphs comprising *Alisporites* sp., *Cyathidites minor*, *?Manumiella* sp., *Microcachryidites antarcticus*, *Peninsulapollis* spp., *Phyllocladidites* spp., *Podocarpidites* sp., *Spinidinium lantern*, *Tricolpites* sp., *Vozzhennikovia apertura*. In situ species included *Impletosphaeridium* spp., *Leiosphaeridia* spp., *Nothofagidites* sp. (*brassii* gp.), *Nothofagidites* sp. (*fusca* gp.), *Nothofagidites* sp. (*menziesii* gp.), *Peninsulapollis* spp., *Phyllocladidites* spp., *Podocarpidites* sp., *Senegalinium asymmetricum*, *Spinidinium macmurdoense*, *Vozzhennikovia apertura*, *Vozzhennikovia rotunda*. This sample is heavily dominated by *Nothofagidites* spp. and *Vozzhennikovia rotunda*.

**La Meseta: sample D6-04 (9 m), Telm7**


**La Meseta: sample D6-05 (12 m), Telm7**

The sample yielded a majority of reworked palynomorphs comprising *Dictyophyllidites* spp., *Foraminisporis* ?dailyi, ?*Manumiella* sp., *Peninsulapollis* spp., *Podocarpidites* sp., *Proteacidites* spp., *Triporopollenites* sp. *In situ* species included *Alterbidinium distinctum*, *Impletosphaeridium* spp., *Leiosphaeridia* spp., *Nothofagidites* sp. (brassii gp.), *Nothofagidites* sp. (fusca gp.), *Podocarpidites* sp., *Proteacidites* spp., *Senegalinium asymmetricum*, *Spinidinium macmurdoense*, *Vozzhennikovia rotunda*.

**La Meseta: sample D6-06 (15 m), Telm7**

The sample yielded a majority of reworked palynomorphs comprising *Dictyophyllidites* spp., *Foraminisporis* ?dailyi, ?*Manumiella* sp., *Nothofagidites* sp. (brassii gp.), *Nothofagidites* sp. (fusca gp.), *Peninsulapollis* spp., *Phyllocladidites* spp., *Podocarpidites* sp., *Proteacidites pseudomoides*, *Pterospermella* spp., *Stereisporites antiquasporites*, *Trilobosporites trioreticulosus*, *Triporopollenites* sp. *In situ* species included *Impletosphaeridium* spp., *Leiosphaeridia* spp., *Myrthaceidites parvus*, *Nothofagidites* sp. (brassii gp.), *Nothofagidites* sp. (fusca gp.), *Nothofagidites* sp. (menziesii gp.), *Phyllocladidites* spp., *Senegalinium asymmetricum*, *Spinidinium macmurdoense*, *Vozzhennikovia rotunda*.

**La Meseta: sample D6-07 (18 m), Telm7**

The sample yielded a majority of reworked palynomorphs comprising *Cyathidites minor*, *Dictyophyllidites* spp., *Foraminisporis* ?dailyi, *Laevigatosporites ovatus*, *Nothofagidites* sp. (brassii gp.), *Nothofagidites* sp. (fusca gp.), *Peninsulapollis* spp., *Phyllocladidites* sp.,

La Meseta: sample D6-08 (21 m), Telm7


La Meseta: sample D6-09 (24 m), Telm7

La Meseta: sample D6-10 (27 m), Telm7

The sample yielded a majority of reworked palynomorphs comprising Laevigatosporites ovatus, Phyllocladidites sp., Podocarpidites sp., Proteacidites spp., Spinidinium lanterna Tricolpites sp., Triporopollenites sp. In situ species were comprised entirely of Impletosphaeridium sp., Leiosphaera spp., Nothofagidites sp. (brassii gp.), Nothofagidites flemingii, Nothofagidites sp. (fusca gp.), Nothofagidites lachlaniae, Peninsulapollis spp., Spinidinium macmurdoense, and Vozzhennikovia spp. In situ species included Leiosphaeridia spp., Spinidinium macmurdoense, Vozzhennikovia rotunda.

La Meseta: sample D6-11 (30 m), Telm7


La Meseta: sample D6-12 (33 m), Telm7

La Meseta: sample D6-13 (36 m), Telm7

The sample yielded a majority of reworked species such as Cyathidites minor, Nothofagidites sp. (brassii gp.) Nothofagidites sp. (fusca gp.), Paleocystodinium golzowenze, Peninsulapollis spp., Phyllocladidites sp., Podocarpidites sp., Spiniferites sp., and Stereisporites ?antiquasporites. *In situ* species included Impletosphaeridium spp., Leiosphaeridia spp.,

La Meseta: sample D6-14 (39 m), Telm7

The sample yielded a majority of reworked species such as Cyathidites minor, Nothofagidites flemingii, Nothofagidites sp. (fusca gp.), Nothofagidites lachlaniae, Paleocystodinium golzowenze., Phyllocladidites sp., Podocarpidites sp., Triclpites sp. *In situ* species included Impletosphaeridium spp., Leiosphaeridia spp.

2.6.2 Palynological results from the Polonez Cove Formation

Unlike La Meseta Formation samples, the Polonez Cove Formation samples contained very few palynomorphs. Abundance of the Polonez Cove rarely exceeded 100 specimens per slide. However, the few species it did contain yielded a mixed group (Plate 7 see appendix B). Most of the specimens analyzed in the Polonez Cove samples were reworked (~85% reworked) (excluding leiospheres), the majority of which were past the point of recognition. The concentrations of *in situ* palynomorphs ranged from 0 to 117 per gram of dried sediments, and the concentrations in reworked palynomorphs ranged from 0 to 73 per gram of dried sediments (Table 2.2), which is drastically lower compared to Oligocene concentrations extending up to 2,000 recovered palynomorphs from the Oligocene section sampled by the SHALDRIL program off the Antarctic Peninsula (Warny and Askin, 2011b). The following information describes the palynological
assemblages identified from the Krakowiak Glacial Member (KGM), Low Head Member (LHM), and the Chlamys Ledge Member (CLM) of the Polonez Cove Formation (Figure 2.4 & 2.5). These members are listed from oldest to youngest, respectively.

Figure 2.4. A. Photograph of the section of the Polonez Cove Formation exposed in the Linton Knoll profile where samples were collected. B. Enlarged section of the Polonez Cove Formation.
Figure 2.5. Detailed lithology of the Polonez Cove Formation and sections where samples were collected during the PAS expedition in 2007 and 2009. * indicates samples were collected from multiple locations containing the Polonez Cove Formation.
Table 2.2. Palynomorph concentrations of reworked (Rw) and *in situ* palynomorphs from the sampled Polonez Cove Formation.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Elevation (m)</th>
<th>Sample recovery</th>
<th>Palynological counts</th>
<th>Concentration of palynomorphs (gdw⁻¹) (Rw)</th>
<th>Concentration of palynomorphs (gdw⁻¹) (in situ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-12</td>
<td>55</td>
<td>Poor</td>
<td>11</td>
<td>41</td>
<td>9</td>
</tr>
<tr>
<td>L-13</td>
<td>48</td>
<td>Poor</td>
<td>7</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>G-13</td>
<td>46</td>
<td>Poor</td>
<td>11</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>L-11</td>
<td>43</td>
<td>Fair</td>
<td>46</td>
<td>9</td>
<td>20</td>
</tr>
<tr>
<td>LHMb</td>
<td>26</td>
<td>Poor</td>
<td>101</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>LHMb</td>
<td>26</td>
<td>Poor</td>
<td>40</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>G8</td>
<td>25</td>
<td>Poor</td>
<td>37</td>
<td>73</td>
<td>44</td>
</tr>
<tr>
<td>LRx</td>
<td>25</td>
<td>Fair</td>
<td>46</td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td>L-6</td>
<td>21</td>
<td>Fair</td>
<td>73</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td>L-5</td>
<td>14</td>
<td>Poor</td>
<td>54</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>K-1</td>
<td>14</td>
<td>Fair</td>
<td>64</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td>KGLMb</td>
<td>7</td>
<td>Poor</td>
<td>95</td>
<td>29</td>
<td>33</td>
</tr>
<tr>
<td>KGLMb</td>
<td>7</td>
<td>Poor</td>
<td>45</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>KGLMb-2</td>
<td>7</td>
<td>Poor</td>
<td>10</td>
<td>7</td>
<td>1</td>
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<tr>
<td>KGLMb-1</td>
<td>7</td>
<td>Poor</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G3</td>
<td>5</td>
<td>Poor</td>
<td>40</td>
<td>44</td>
<td>117</td>
</tr>
</tbody>
</table>

Krakowiak Glacial Member

Specimens analyzed throughout the KGM (excluding leiospheres and a few other species of palynomorphs) were mostly comprised of reworked palynomorphs and filled with charred organic matter indicative of volcanic activity. The majority of reworked species are most likely species that are Jurassic to Cretaceous in age. They included reworked species of *Calamospora* sp., *Cyathidites minor*, *Deflandrea* sp., *Diconodinium* sp., *Dictyophyllidites* sp., ?*Microcachryidites antarcticus*, *Myricipites* sp., *Odontochitina operculata*, *Peninsulapollis gillii*, *Phyllocladidites* sp., *Podocarpidites* spp., *Triporopollenites* sp. *In situ* species included *Chenopodipollis* sp., *Haloragacidasites* sp., *Leiosphaeridia* spp., *Nothofagidites* sp. (fusca gp.),
Phyllocladidites mawsonnii, Podocarpidites spp., Reticulatosphaera actinocornata, Triporopollenites sp.

**Low Head Member**

The Low Head Member of the Polonez Cove Formation consisted of mostly reworked specimens and a plethora of volcanic material. The species were difficult to identify, but consisted mostly of reworked *Calamospora* sp., *Chenopodipollis* sp., *Cyathidites minor*, *Dictyophyllidites* sp., *Haloragacidites* sp., *?Microcachryidites antarcticus*, *Myricipites* sp., *Nothofagidites* sp. (fusca gp.), *Odontochitina operculata*, *Peninsulapollis gillii*, *Podocarpidites* sp., *Stelliopollis annulatus*, and *Triporopollenites* sp. *In situ* species consisted of *Chenopodipollis* sp., *Leiosphaeridia* spp.

**Chlamys Ledge Member**

The final section is the Chlamys Ledge Member. This member was comprised of reworked species of *Calamospora* spp., *Cyathidites minor*, *Haloragacidites* sp., *Myricipites* sp., *Phyllocladidites* sp., *Podocarpidites* sp. *Stereisporites antiquasporites*, and *Tricolpites gillii*. *In situ* species included *Impletosphaeridium* sp., *Leiosphaeridia* spp.

2.7 **Discussion**

2.7.1. **Paleoenvironmental interpretation of recovered palynomorphs**

To determine paleoenvironmental conditions, species analyzed from the assemblages were identified as being either reworked or *in situ*. When age-restricted species older than Eocene or Oligocene were found (e.g., the frequent Cretaceous species recovered), they were easily recognized as reworked. However, for species with longer age ranges, it is sometimes difficult to
distinguish reworked from *in situ*. This is because the spore and pollen’s highly resistant exine polymer (sporopollenin) is capable of withstanding heat, aging, and some depositional pressure, which keeps the grain intact (Dickinson, H.G. and Heslop-Harrison, J., 1968). When stratigraphic ranges were too long to determine the reworking status, the preservation of the grains as well as the thermal maturity of their wall were considered. Figures 2.6 and 2.7 summarize the overall abundance of palynomorphs observed and show our interpretations of reworked vs. *in situ* species from both La Meseta Formation and Polonez Cove Formation. A detailed analysis of reworked vs. *in situ* palynomorphs from La Meseta and Polonez Cove formations are shown in Figures 2.8 and 2.9, respectively.

![Figure 2.6. Overall abundance of palynomorph species observed in the La Meseta Formation of Seymour Island where red=*in situ* and pink=reworked.](image)

Amongst the La Meseta Formation samples analyzed, a trend showing a passage from predominantly *in situ* specimens in samples D6-01 to D6-06, to an increase in reworked specimens
from samples D6-07 to D6-14 was observed. By mid-Oligocene, the Polonez Cove Formation was almost exclusively composed of reworked palynomorphs (Figure 2.6 & 2.8). The abundance of in situ species, from the lower section of the sampled La Meseta formation, predominantly included leiospheres, *Podocarpidites* sp., *Phyllocladidites* sp., *Nothofagidites* sp. (*brassii* gp.), and *Nothofagidites* sp. (*fusca* gp.). The *Podocarpidites* sp. and *Phyllocladidites* sp. are types of conifers that typically thrive in cool, temperate, climates. *Nothofagidites* sp. (*fusca* gp.) is also typically found in cooler more temperate environments. By observing an assemblage of in situ *Podocarpidites* sp., *Phyllocladidites* sp., *Nothofagidites* sp. (*brassii* gp.), and *Nothofagidites* sp. (*fusca* gp.) at the basal section of our La Meseta sample set, we can infer the environment was comparable to a cool, temperate, Valdavian-type forest, found in parts of modern day Chile, up to the time of sample D6-06. After sample D6-06, the increased relative abundance of both reworked species and the in situ sea-ice indicative leiospheres together infer a less vegetated, more glacially dominated, environment from the time of deposition of sample D6-07.
Figure 2.7. Overall abundance of palynomorph species observed in the Polonez Cove Formation samples from King George Island. Red=\emph{in situ} and pink=reworked.

Although our sampling did not include the Early Oligocene, the mid to Late Oligocene sections studied in the Polonez Cove indicated that by that time, on the other side of the Antarctic Peninsula, vegetation was reduced to sparse occurrences consisting mostly of herbaceous plants with some southern beech and podocarp conifers. The fact that leiospheres were largely abundant indicates sea-ice was still present and mostly dominated the area off the Peninsula. Figures 2.7 & 2.9 highlight how the overall abundance, diversity and preservation of palynomorphs have greatly diminished compared to those of La Meseta Formation: This is a conclusion congruent with the results from the 2006 SHALDRIL campaign (Anderson et al., 2011; Warny and Askin, 2011b). The vast majority of the observed palynomorphs in these samples were reworked. Though the
occasional *in situ* terrestrial palynomorphs were witnessed, the majority of *in situ* palynomorphs consisted of *Leiosphaeridia* spp., a group often associated with the sphaeromorph acritarchs, and *Impletosphaeridium* spp., a group of dinocysts. These *Leiosphaeridia* spp. are known to be abundant at the limit between pack ice and sea ice (Mudie, 1992; Troedson and Riding 2002; Warny et al., 2006). Similar to *Leiosphaeridia* spp., *Impletosphaeridium* spp. are believed to be present during sea-ice formation (Warny et al., 2007).

Figure 2.8. Relative abundance of reworked (Rw) and *in situ* palynomorphs in these La Meseta Formation samples.
2.7.2. Palynological response compared with previous studies

Dating for the La Meseta Formation has been determined through the years of paleontological and isotopic analyses. These analyses included the use of vertebrate (Simpson, 1971; Gelfo et al., 2015) and mollusk fossils (Zinsmeister, 1977; Elliot & Trautman, 1982) and palynological studies (Hall, 1977; Askin & Flemming, 1982; Wrenn & Hart, 1988; Askin et al., 1991), which concluded a general age ranging between Early Eocene at the base to Late Eocene at the uppermost section of the La Meseta Formation. Recent strontium-isotope analyses were conducted on *Cucullaea* specimens collected throughout the Submeseta allomember (Telm1-Telm7) of the La Meseta Formation and supported the previously assigned age range of Early Eocene to Late Eocene (Dutton & Lohmann, 2002 and references therein). Specifically, the Dutton & Lohmann study placed the upper most section of La Meseta Formation’s Telm7 between 34-36 Ma. The last occurrence datum (LAD) for *Vozzhennikovia rotunda* and *Spinidinium*

Figure 2.9. Relative abundance of reworked (Rw) and *in situ* palynomorphs in these Polonez Cove Formation samples.
macmurdense observed in our samples confirmed an Eocene age and narrowed the Telm7 range to 33.7 to 37 Ma (Wrenn & Hart, 1988; Williams et al., 2003).

Dating for the Polonez Cove Formation has been determined through strontium-isotope dating of mollusk fossils (Dingle et al., 1997; Dingle & Lavelle, 1988) and $^{40}$Ar/$^{39}$Ar dating of interbedded basaltic lava flows (Smellie et al., 1998; Troedson & Smellie, 2002). These results yielded a middle to late Oligocene age. Specifically, results from the Sr-isotope ages ranged between 28.5-29.8±0.8 Ma. $^{40}$Ar/$^{39}$Ar ratios from basalt lava, collected from the Low Head Member and southern Mazurek Point, ranged between 26.0±2.59 Ma and 25.6±1.3 Ma, respectively (Dingle & Lavelle, 1988; Dingle et al., 1997). Unlike the La Meseta Formation, biostratigraphic markers were absent from the observed samples, making an age constraint based solely on isotopic dating. By using the age overlap of the above data, it is believed that the studied samples from the Polonez Cove Formation are ~26-28 Ma.

Although the age constraint from the aforementioned overlapping data could only narrow the uppermost La Meseta Formation to 34-36 Ma and the Polonez Cove Formation to ~26-28 Ma, palynological results from these sampled intervals provided a general understanding of the climatic changes that occurred in the Antarctic Peninsula during these times. Observations of the sampled intervals revealed palynomorph status changed from mostly in situ in the older section of the uppermost La Meseta Formation and progressively became more reworked. This trend of increasingly reworked palynomorphs continued into the Polonez Cove Formation where the majority of palynomorphs were comprised of reworked species. The abundance of reworked palynomorphs coupled with the large occurrence of Leiosphaeridia spp., which increased from the youngest samples of the La Meseta Formation to the Polonez Cove Formation, indicate the Latest Eocene was already cool and continued to cool into the Oligocene. This palynological response
is supported is with shifts in the $\delta^{18}$O curve which indicated temperatures cooled in the Latest Eocene and continued throughout the Oligocene (Figure 2.10).

Figure 2.10. Stratigraphic position of sampled La Meseta Formation and Polonez Cove Formation in relation to the $\delta^{18}$O global climate. Age of sampled interval for the La Meseta Formation was determined based on the overlap of LAD of observed biostratigraphic markers ($Vozzhennikovia. rotunda$ and $Spinidinium macmurdoense$) and Sr-isotope analyses in Dutton & Lohmann, (2002). Age of sampled interval for the Polonez Cove Formation was determined based on the overlap of Sr-isotope dating in Dingle & Lavelle, (1988) and Dingle et al., (1997) and $^{40}$Ar/$^{39}$Ar dating in Smellie et al., (1998) and Troedson & Smellie, (2002). Modified from Zachos et al., (2008).
2.8 Conclusions

The samples collected from La Meseta Formation on Seymour Island, and the Polonez Cove Formation on King George Island provide insight into the climatic evolution that occurred at the latest Eocene and in the mid to Late Oligocene in the Antarctic Peninsula. Dinoflagellate cyst biostratigraphy confirms an Eocene age for the youngest part of the La Meseta Formation. Our results revealed that this latter stage of the Eocene so-called “green-house” climate was already experiencing cooler climatic conditions as seen in the low diversity of in situ Podocarpidites sp., Phyllocladidites sp., Nothofagidites sp. (brassii gp.), and Nothofagidites sp. (fusca gp.) taxa recovered from the basal section (samples D6-01 through D6-06). The “green-house” latest Eocene conditions were in fact more similar to, cool, temperate, Valdivian-type forest. These conditions started to become even cooler in the top of La Meseta as evidenced by increased abundance in reworked species and sea-ice indicative marine phytoplankton in samples D6-07 to D6-14. The fact that our data show cool climate conditions during the latest Eocene is further supported by data presented from other studies across Antarctica which describe cool conditions occurring during the latest Eocene (e.g. cores from Prydz Bay in Hambrey et al., 1991 and erratics from McMurdo Sound in Askin, 2000). By the mid to Late Oligocene, as evidenced by a mostly reworked assemblage found in the Polonez Cove Formation samples and abundance of sea-ice indicative species, the Peninsula was well into an ice-covered environment with extremely reduced vegetative cover.
2.9 Acknowledgments

The authors would like to thank the Institute of Geological Sciences, Polish Academy of Sciences for providing the Polonez Cove samples. Field assistance of Marcin Klisz and Mariusz Potocki during 2007 expedition and Grzegorz Zieliński during 2009 expedition is greatly appreciated. Fieldwork was financially supported by the Polish Ministry of Science and Higher Education (Grant No. DWM/N8IPY/2008). This is a contribution to the Antarctic Climate Evolution (ACE) program.

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CHAPTER 3. CONCLUSION

The results presented in this thesis help to shed new light on Antarctic earth science and the climate that was present from the Late Eocene to the Early Miocene. Palynological assemblages observed in the samples collected from the Late Eocene La Meseta Formation reveal climate was already experiencing cooler conditions prior to the EOT. This was observed from the low diversity of *in situ* Podocarpidites sp., Phyllocladidites sp., Nothofagidites sp. (*brassii* gp.), and Nothofagidites sp. (*fusca* gp.) taxa witnessed in the lower section (D6-01 through D6-06), which is similar to a cool temperate type forest found in modern day Chile, and Argentina. However, Antarctic climate continued to decline into the youngest section of the La Meseta Formation (D6-07 through D6-14) as indicated by the reworked palynomorphs and sea-ice indicative *Leiosphaeridia* spp., which progressively became more abundant. This palynological interpretation of Antarctica’s vegetation response to climate shifts from a cool-temperate climate to one much cooler coincides with evidence of cooler conditions, prior to the EOT, seen in other studies that have been conducted on Late Eocene sections across Antarctica (e.g. Hambrey et al., 1991; Askin, 2000; Anderson et al., 2011; Warny and Askin, 2011a).

Although palynomorph abundance was not as prominent or as diverse as in the La Meseta samples, the assemblages observed in the Polonez Cove Formation samples yielded valuable results. The palynomorphs from these samples were mostly reworked with the exception of the occasional *in situ* Podocarpidites sp. and Nothofagidites spp. The majority of the species that were *in situ*, and dominated the samples, were the sea-ice indicative *Leiosphaeridia* spp. These results indicate climate was much cooler than that of the Eocene epoch and the large presence of *Leiosphaeridia* spp., and mostly reworked species of palynomorphs, indicates glaciation had already occurred in the Antarctic Peninsula by the Middle Oligocene.
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APPENDIX

Palynological plates used for Late Eocene and Middle Oligocene palynology and climate trends in the Antarctic Peninsula

Plate 1. Light photomicrographs of dinoflagellate cysts specimens from the upper La Meseta Formation, Seymour Island, Antarctica. All images were taken at 60x. Black bar measures 20 μm. 1. Vozzhennikovia rotunda (sample D6-01 6.3x117.8) in situ, 2. Vozzhennikovia apertura (sample D6-03 16.0x139.1) in situ, 3. Spinidinium macmurdoense (sample D6-12 14.6x144.9) in situ, 4. Spinidinium cf. macmurdoense (sample D6-02 6.4x142.0) in situ, 5-7. Senegalinium asymmetricum (5. Sample D6-11 17.3x142.3; 6. Sample D6-09 14.1x144.4; 7. Sample D6-08 15.0x139.8) in situ, 8. Spinidinium lanterna (sample D6-11 17.3x145.4) reworked, 9. ?Manumiella sp. 3 (sample D6-05 15.1x138.7) reworked.
Plate 2. Light photomicrographs of dinoflagellate cysts specimens from the upper La Meseta Formation, Seymour Island, Antarctica. All images were taken at 60x. Black bar measures 20 μm. 1. *Paleocystodinium golzowense* (sample D6-13 15.4x138.2) reworked, 2. *Phelodinium* sp. (sample D6-13 15.4x138.2) reworked, 3. *Diconodinium cristatum* (sample D6-04 6.5x119.3) reworked.
Plate 3. Light photomicrographs of trilete spores from the upper La Meseta Formation, Seymour Island, Antarctica. All images were taken at 60x. Black bar measures 20 μm. 1-2. *Cyathidites minor* (1. Sample D6-13 15.3x142.0; 2. Sample D6-03 7.8x127.2) *in situ*, 3. *Laevigatosporites ovatus* (sample D6-01 11.5x116.3) *in situ*, 4. *Acanthotriletes teretangulatus* (sample D6-05 4.2x146.0) reworked, 5. *Leiotriletes directus* (sample D6-01 13.5x138.8) reworked, 6. *Clavifera triplex* (sample D6-02 6.4x143.8) reworked, 7. *Punctatissorites* sp. (sample D6-01 4.8x132.1) reworked, 8. *Dictyophyllidites* sp. (sample D6-06 11.9x133.6) reworked, 9. *Punctatissorites* sp. (sample D6-01 4.9x144.2) reworked.
Plate 4. Light photomicrographs of gymnosperm specimens from the upper La Meseta Formation, Seymour Island, Antarctica. All images were taken at 60x. Black bar measures 20 μm. 1. *Phyllocladidites* sp. Cf. *P. exiguous* (sample D6-08 13.3x147.6) in situ, 2-4. *Phyllocladidites* sp. (2. Sample D6-05 15.1x138.7; 3. Sample D6-09 16.5x135.9; 4. Sample D6-08 13.4x148.5) reworked, 5. Large bisaccate is a taeniate *Protohaploxypinus* sp. (sample D6-13 15.2x140.6) reworked, 6. *Phyllocladidites* ?mawsonii (sample D6-03 3.7x133.1) reworked, 7. *Alisporites* sp. (sample D6-03 3.9x128.0) reworked.
Plate 5. Light photomicrographs of angiosperms from the upper La Meseta Formation, Seymour Island, Antarctica. All images were taken at 60x. Black bar measures 20 μm. 1. *Myricipites harrisii* (sample D6-01 14.2x119.4) *in situ*, 2. *Proteacidites* sp. Cf. *P. parvus* (sample D6-01 13.4x143.9) *in situ*, 3. *Peninsulapollis askiniae* (sample D6-09 16.2x147.3) *in situ*, 4. *Peninsulapollis gillii* (sample D6-03 3.4x144.4) *in situ*, 5-8. *Proteacidites* spp. (5. Sample D6-03 8.0x142.7 (*in situ*); 6. Sample D6-03 8.0x143.4 (*in situ*); 7. Sample D6-05 4.2x139.8 (*in situ*); 8. Sample D6-03 i.0x130.9 (reworked)), 9. *Proteacidites* sp. (sample D6-02 6.5x128.7) reworked, 10. *Propylipollis subscabratus* (sample D6-02 6.5x128.7) reworked, 11. *Proteacidites* sp. (sample D6-10 17.3x132.2) reworked, 12. *Proteacidites* sp. (sample D6-08 13.7x142.5) reworked.
Plate 6. Light photomicrographs of Nothofagidites spp. angiosperms from the upper La Meseta Formation, Seymour Island, Antarctica. All images were taken at 60x. Black bar measures 20 μm. 1. Nothofagidites mataurensis (sample D6-05 4.1x143.5) in situ, 2. Nothofagidites sp. (sample D6-05 14.2x140.6) in situ, 3-5. Nothofagidites rocaensis-saraensis complex (3. Sample D6-05 14.4x136.2; 4. Sample D6-08 15.9x141.7; 5. Sample D6-09 16.2x139.1) in situ, 6-8. Nothofagidites sp. Cf. N. asperus (6. Sample D6-11 15.5x117.5; 7. Sample D6-01 6.4x120.4; 8. Sample D6-01 11.4x113.6) in situ, 9. Nothofagidites lachlaniae (sample D6-03 15.9x134.6) reworked, 10-16. Nothofagidites rocaensis-saraensis complex (10. Sample D6-07 13.2x141.8; 11. Sample D6-11 15.5x125.3; 12. Sample D6-01 11.5x131.1; 13. Sample D6-05 14.9x137.3; 14. Sample D6-05 6.1x125.5; 15. Sample D6-12 14.8x143.2; 16. Sample D6-09 13.2x121.8) reworked.
Plate 7. Light photomicrographs of mostly reworked samples collected from the Polonez Cove Formation, King George Island, Antarctica. All images were taken at 60x. Black bar measures 20 μm. 1-2. *Leiosphaeridia* spp. (1. Sample G-13 12.1x141.0; 2. Sample KGLMb-2 10.7x137.6) in situ, 3-4. *Nothofagidites rocaensis-saraensis* complex (3. Sample K-1 17.8x116.4; 4. Sample K-1 17.8x128.4) reworked, 5. *Cyathidites minor* (sample K-1 14.6x131.7) reworked, 6. *?Haloragacidites* sp. (sample L-5 8.1x132.9) reworked, 7. *Podocarpidites* sp. (sample L-5 11.1x133.1) reworked, 8. *Reticulatosphaera actinocoronata* (sample K-1 9.3x121.1) in situ, 9. *Diconodinium* sp. (sample KGLMb 13.9x143.1) reworked.
VITA

Madison Kymes was born in Shreveport, Louisiana but spent the majority of his life in Madison, Mississippi. He graduated from Louisiana State University in Baton Rouge, Louisiana in 2013 with a B.S. in Geology and a minor in Anthropology. After completing his Master’s, he plans to pursue a job in environmental geology.