

Vegetation and Organic-Walled Phytoplankton at the End of the Antarctic Greenhouse World: Latest Eocene Cooling Events

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The NBP0602A-3C SHALDRIL section collected in the Weddell Sea recovered a key stratigraphic interval that captured the response of plants and organic-walled phytoplankton during the first marked increase in $\delta^{18}\text{O}$ followed by the large reduction in atmospheric CO_2 in the late Eocene around 36 Ma. Well-preserved palynomorphs recovered from in situ shelf sediments provide evidence of a cooling event followed by a marked sea level drop around 36 Ma. Terrestrial palynomorphs indicate that at the time of deposition, southern beech-dominated and conifer forest vegetation was abundant but with lower diversity and signifying colder climates than for most of the La Meseta Formation on Seymour Island. The marine palynomorph assemblage is dominated by *Vozzhennikovia apertura*. This low-diversity, high-dominance dinoflagellate cyst assemblage is also a sign of deteriorating conditions. Particularly notable is the marked increase in the uppermost Eocene samples of reworked dinoflagellates and acritarchs of Cretaceous age. This suggests significant erosion and redeposition of nearby Campanian-Maastrichtian sections during a marked drop in sea level. Based on the biostratigraphy and a single isotopic date, it is likely that the cooling and subsequent lowering of sea level can be correlated to the brief spike in $\delta^{18}\text{O}$ -enriched values shown by the Zachos et al. (2001) curve in the Priabonian. According to Zachos et al. (2008), this event occurs at a time when lowest carbon dioxide atmospheric concentrations were between 600 and 980 ppmv, giving us some perspectives as to what could be expected when the current CO_2 atmospheric concentration is at least doubled.

1. INTRODUCTION

Palynological investigations in Antarctica have been one of the primary means of elucidating shifts in past Antarctic climate [Warny *et al.*, 2006, 2009; Thorn *et al.*, 2009; Anderson *et al.*, 2011]. One such climatic shift of interest is when and how the climate evolved from greenhouse to icehouse conditions around the Eocene-Oligocene boundary, approximately 33.7 Myr ago. To refine our understanding of this important transition, one of the goals of the SHALDRIL II campaign was to drill through a section believed to be composed of in situ sediment that recorded changing climatic conditions across the Eocene-Oligocene boundary, and Borehole NBP0602A-3C was acquired. This chapter focuses on the palynological results of SHALDRIL II Borehole NBP0602A-3C, northern Antarctic Peninsula. We summarize and discuss recovered terrestrial fossil palynomorphs (pollen and spores), which help reconstruct past vegetation and thus paleoclimate, and marine palynomorphs (mostly dinoflagellate cysts and acritarchs), which are useful proxies for reconstructing sea-surface conditions such as sea-surface salinities, sea-surface temperature, and sea ice cover. Although palynomorph recovery is highly variable in many Eocene to recent Antarctic marginal strata, assemblages recovered are extremely valuable for detailed biostratigraphic and paleoenvironmental reconstruction. For instance, Mao and Mohr [1995], thanks to exceptionally rich dinocyst assemblages from Bruce Bank, were able to estimate winter surface water paleotemperatures at about 5°C to 10°C and summer temperatures reaching more than 14°C for the Neogene climatic optimum. Warny *et al.* [2009] highlighted the existence of a short and sudden warm climatic event 15.7 Myr ago, based on marine and terrestrial palynomorphs recovered from ANDRILL-2/2A in the Ross Sea. In this study, palynomorph assemblages provided further quantitative data of what the environment in Antarctica was like during the Mid-Miocene Climatic Optimum. They indicated that annual sea-surface temperatures ranged from 0°C to 11.5°C, land temperatures reached 10°C (January mean), and an increase in meltwater (and possibly rainfall) producing ponds and lakes adjacent to the Ross Sea developed during a short period of sea ice reduction.

In applying similar techniques to the SHALDRIL NBP0602A-3C section, a primary focus of the current study was to determine if major environmental changes were manifested first by changes of climate on land (this would be visible in terrestrial palynomorph changes), or did the changes occur first in the marine realm (as would be visible in changes in dinoflagellate cyst and acritarch assemblages), or were the changes occurring concurrently on land and in the ocean? One fundamental question we posed ourselves was “Did sea-surface cooling precede climate (land) cooling?” Better constraining the timing of these environmental changes both in the terrestrial and marine realms would help us better understand the source of these changes. The assumption here is that if opening of ocean passages were the main factor driving Antarctic climate change [Kennett, 1977], then thermal isolation would have affected dinocysts first since these organisms are directly influenced by ocean currents. Conversely, if decreased atmospheric CO₂ was the main control on the cryosphere’s development [DeConto and Pollard, 2003], then initial cooling should have affected land plants first. If both marine and terrestrial organisms are affected at the same time, within limits of resolution, then one might conclude that the end of the greenhouse world was a consequence of both gateway closure and lower concentration in atmospheric carbon dioxide, with both factors possibly interrelated.

2. MATERIAL AND METHODS

Borehole NBP0602A-3C’s location was selected specifically because seismic profiles show a series of basinward-tilted sedimentary deposits truncated at/near the seafloor. These strata were estimated to range from upper Eocene to upper Neogene in age [Anderson, 1999; Anderson *et al.*,

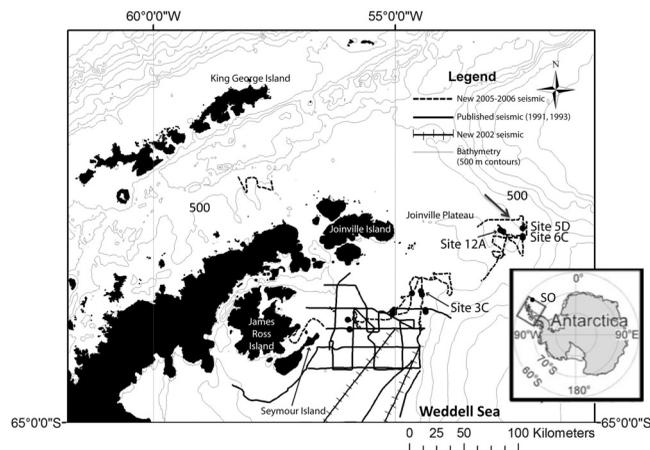


Figure 1. Location of SHALDRIL NBP0602A-3C drill hole off James Ross Island, Weddell Sea, Antarctica. From *Anderson et al.* [2011].

2006; *Anderson et al.*, 2011]. Based on these seismic data, Anderson and colleagues concluded that the Eocene section should be accessible at relatively shallow depth as recent glacial erosion exposed this stratigraphic section below a thin (less than one meter) glacial unit deposited at the seafloor. This section was thus a prime target for a SHALDRIL-type drilling campaign.

Borehole NBP0602A-3C was drilled at $63^{\circ}50.861'S$ latitude and $54^{\circ}39.207'W$ longitude and sampled the strata immediately offshore and downdip of James Ross Island in the Weddell Sea (Figure 1). This hole is composed of a series of seven drilled sections or cores with intervals of low to no recovery in between. Continuous coring was made impossible by extremely harsh weather conditions and fast-moving sea ice at the time of drilling. The core units are consecutively named core NBP0602A-3C-1 from the top of the section to core NBP0602A-3C-7 at the base. Figure 2 presents a summary of the zone of recovery and the relationship between each unit with respect to depth below seafloor [*Bohaty et al.*, this volume]. By convention, recovered core has been placed at the top of each cored interval. This plate also presents a summary of the onboard diatom zonal assignment and diatom age determination [*Bohaty et al.*, this volume]. Based on preliminary diatom biostratigraphy, units in core NBP0602A-3C-7 to most of core NBP0602A-3C-1 were assigned a maximum age of 37 Ma and a minimum age of 32 Ma, with, disconformably overlying them, a thin (less than 1 m) upper Pleistocene- to Holocene-recovered section marking the top of core NBP0602A-3C-1. Sample NBP0602A-3C-1, containing 100% reworked polymorphs, is not discussed. Based on the diatom age, it was confirmed that the section sampled was therefore uppermost Eocene to lowermost Oligocene.

Based on their seismic stratigraphic analysis, *Anderson et al.* [2006] noted that, given the great thickness of the total sediment package present at this site, the ~ 10 m thick section sampled in Hole NBP0602A-3C must only represent a very short interval of time within the assigned age range. Furthermore, the sediments from this hole mostly consist of muddy to very fine sand that varies in color from greenish black in the upper portion of the hole (0–7.5 mbsf) to very dark greenish gray in the lower portion (7.5–20.0 mbsf) of the core [*Anderson et al.*, 2006]. So, it is assumed that the section recovered is essentially continuous, but a minor hiatus might be present around 7.5 mbsf.

Twenty samples were collected for palynological analysis. Location of palynological samples relative to the various core units recovered is indicated in Figure 2. As marked in this plate, two to three samples were taken at regular intervals in each of the cored units recovered from NBP0602A-3C-1 to NBP0602A-3C-7. The detailed location of these samples can be found in Table 1.

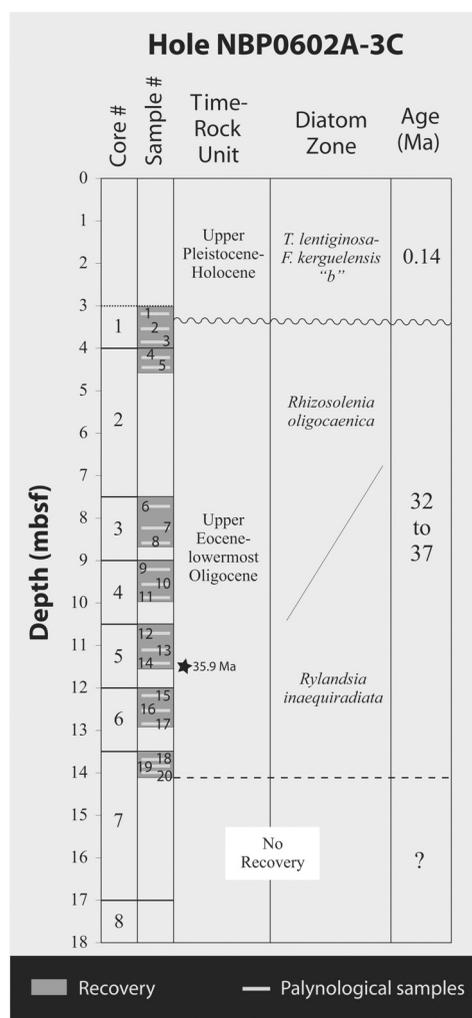


Figure 2. Palynological sample location in relation to the diatom zonal assignments and age interpretation for Borehole NBP0602A-3C. Note that sample 1 is of upper Pleistocene-Holocene age. Modified after Figures 4–6 of the Shipboard Scientific Party (SHALDRIL II 2006 NBP0602A cruise report, 2006, available at http://www.arf.fsu.edu/projects/documents/Shaldril_2_Report.pdf, hereinafter referred to as Shipboard Scientific Party, 2006).

These samples were chemically processed following a palynological technique based on a mix of traditional methods such as those summarized by *Brown* [2008]. For each sample, about 10 g of dried sediments were weighed (the precise weight for each sample is listed in Table 1). This weight is important as it is used to calculate palynomorph concentration per gram of dried sediment to allow evaluation of changes in concentration throughout the core. The sediment was then spiked with a known quantity of *Lycopodium* spores to allow computation of the absolute abundance of palynomorphs in the sample. Acid soluble minerals were digested in HCl and HF acid to remove carbonates and silicates. The palynomorphs were then concentrated by filtration on a 10 μm mesh sieve. Samples were sufficiently rich to allow the tabulation of 300 palynomorphs per sample. A database of all palynomorphs recovered was prepared, and key species were photographically documented.

Table 1. Details of Sampled Core Sections of NBP0602A-3C

Sample	Depth of Sample per Core Section (cm)	Weight (g)	Dinocyst Concentration	Pollen Concentration (specimen per gram of dried sediments)
<i>Core Section NBP0602A-3C-1</i>				
1	14–16	13.4	23300	700
2	54–56	15	1800	2,100
3	88–90	15	2400	1,100
<i>Core Section NBP0602A-3C-2</i>				
4	10–12	11.6	4800	2,200
5	29–31	10	16300	3,800
<i>Core Section NBP0602A-3C-3</i>				
6	11–13	10	9100	10,800
7	59–61	10.1	9800	8,100
8	95–97	10.1	3000	3,300
<i>Core Section NBP0602A-3C-4</i>				
9	10–12	10	8400	6,100
10	49–51	10	6600	30,800
11	85–87	10	4800	3,500
<i>Core Section NBP0602A-3C-5</i>				
12	10–12	10	11800	13,900
13	54–56	10	18000	19,000
14	81–83	6.5	18700	33,300
<i>Core Section NBP0602A-3C-6</i>				
15	10–12	10	16700	14,200
16	49–51	8	92000	100,000
17	83–85	8	55000	44,700
<i>Core Section NBP0602A-3C-7</i>				
18	6–8	8	26600	33,500
19	29–31	8	30600	21,700
20	57–59	8	103300	75,300

Repository and curation of all palynological slides will be handled by the Louisiana State University Center for Excellence in Palynology (CENEX).

3. PALYNOLOGICAL RESULTS

3.1. General Evaluation

Well-preserved penecontemporaneous terrestrial and marine palynomorphs, as well as recycled palynomorphs, were recovered. The concentration of dinoflagellate cysts per gram of dried sediments (d/g) and pollen and spores were calculated and graphically represented (Figure 3). The

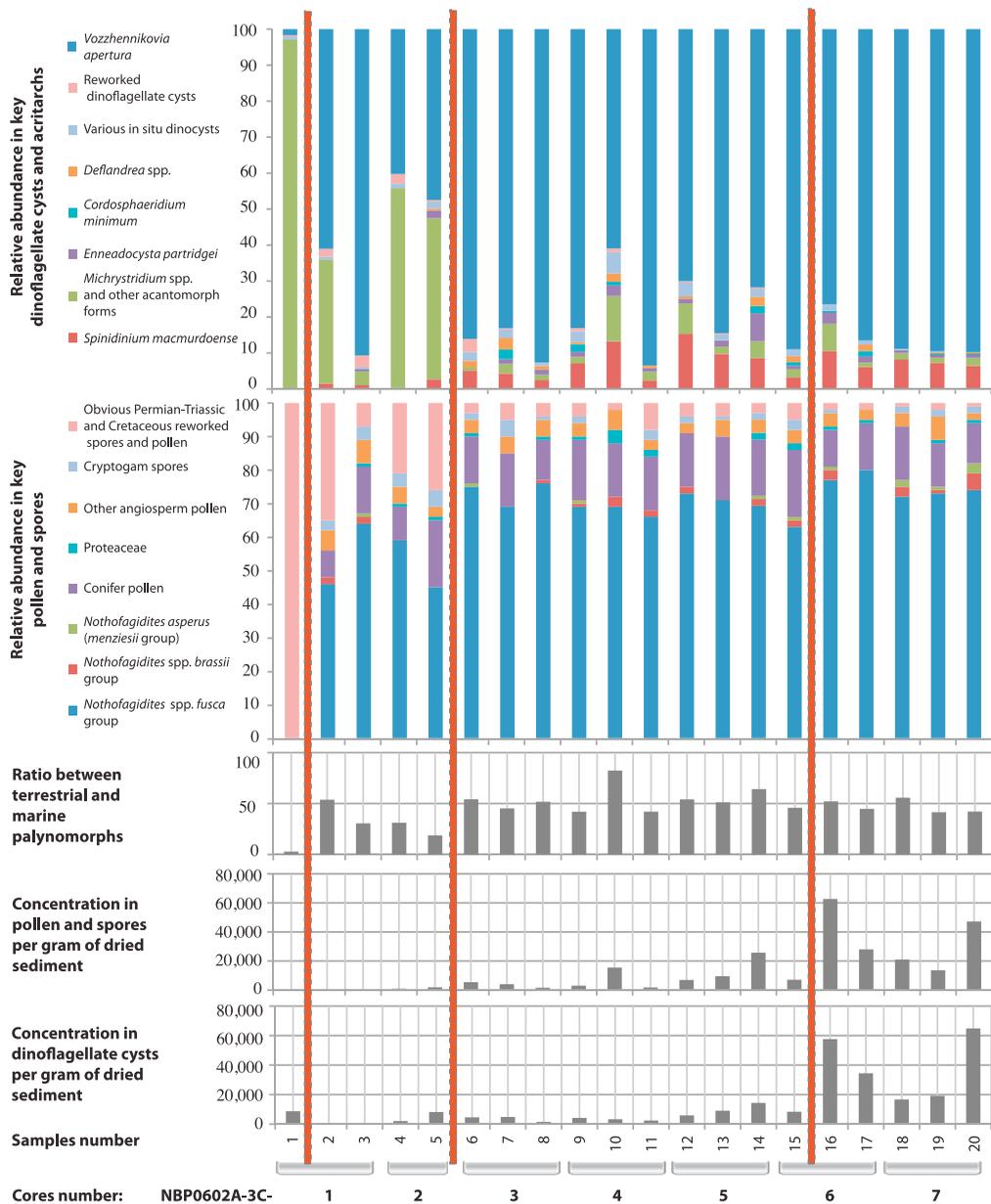


Figure 3. Relative abundance in key palynomorphs, concentration in palynomorphs per gram of dry sediment and ratio between terrestrial and marine palynomorphs, related to sample and core numbers.

concentrations of dinoflagellate cysts per gram of dried sediments (d/g) range from a high maximum of 64,800 d/g in the bottom of the core to a minimum 600 d/g in the top of the core. The concentrations of pollen and spores per gram of dried sediments (p/g) range from quite good 47,200 p/g in the bottom of the core to a low 700 p/g in the top of the core, with a maximum of 62,700 p/g in sample 16 (NBP0602A-3C-6-49) and a minimum of 400 p/g in sample 3 (NBP0602A-3C-1-88).

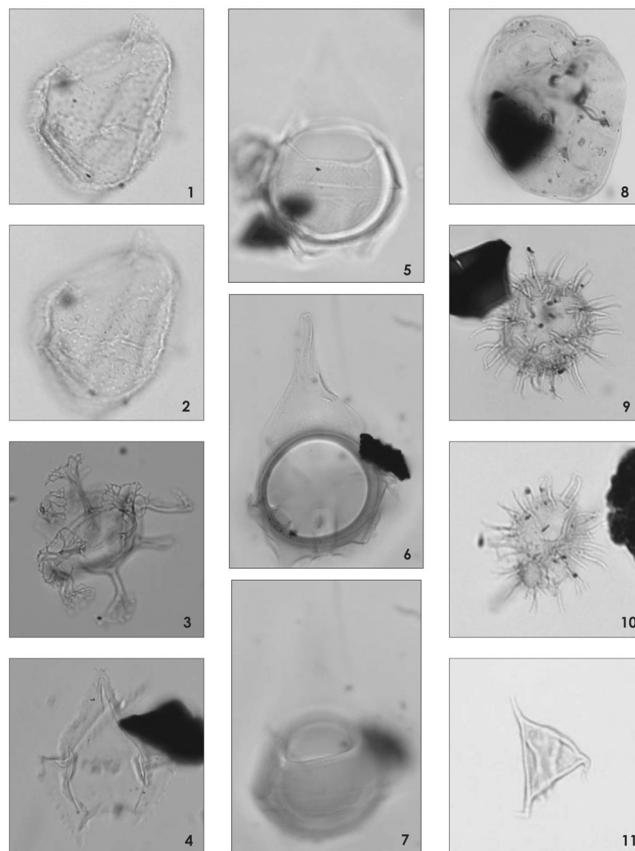


Figure 4. Light photomicrographs of key species of dinoflagellate cyst and acritarch. For each sample, the sample number (e.g., NBP0602A-3C-1) is followed by the sample depth (e.g., 0.54) and then by the England Finder coordinates of each specimen. Numbers represent the following: 1 and 2, *Vozzhennikovia apertura*, NBP0602A-3C-1.54, V41/3; 3, *Enneadocysta partridgei*, NBP0602A-3C-5.10, T43/1; 4, *Spinidinium macmurdoensis*, NBP0602A-3C-1.54, U21/4; 5, *Deflandrea antarctica*, NBP0602A-3C-4.49, P42/3; 6 and 7, *Deflandrea cygniformis*, NBP0602A-3C-4.85, Q29/4; 8, *Manumiella seymourensis*, NBP0602A-3C-1.54, P41/4; 9, *Micrhystridium* sp., NBP0602A-3C-1.14, V33/4; 10, *Impletosphaeridium?* sp. (note archeopyle), NBP0602A-3C-1.14, U27/4; and 11, *Veryhachium reductum*, NBP0602A-3C-3.59, N44/3.

Interestingly, after relatively constant high concentrations of both marine and terrestrial palynomorphs from samples 20 through 16, a sharp decrease in concentration is observed, with concentrations remaining low from samples 15 to 2 (Figure 3). This significant sudden drop in concentration of ~85% for marine palynomorphs and of ~90% in terrestrial palynomorphs could reflect a sharp decline in plant and phytoplankton productivity resulting from a major shift toward colder climatic conditions, felt both on land and in the marine realm. But this signal could also be induced by a higher sedimentation rate that would give the appearance of lower plant and phytoplankton productivity, while simply associated with increased terrigenous input.

3.2. Dinoflagellate Cysts and Acritarchs

The relative abundances of key dinoflagellate and acritarch species are presented in Figure 3. Key dinoflagellate and acritarch species are illustrated in Figure 4. The marine palynomorph

assemblage in most samples is dominated by *Vozzhennikovia apertura*. That species is relatively frequent throughout the La Meseta Formation on Seymour Island [Wrenn and Hart, 1988], especially at Cape Wiman [Cocozza and Clarke, 1992]. It has also been reported as a common component of the assemblage in the Eocene Southern Ocean [Sluijs *et al.*, 2003; Brinkhuis *et al.*, 2003]. However, in all instances, none of these authors reported such dominance in *V. apertura* in the assemblage. Other species recorded in NBP0602A-3C borehole are *Enneadocysta partridgei*, *Deflandrea antarctica* along with specimens of *Deflandrea cygniformis* and *Deflandrea phosphoritica*, *Spinidinium macmurdoensis*, and *Cordosphaeridium minimum*. *Vozzhennikovia rotunda* was found in a few samples but only as rare occurrences. All of these are typical high southern latitude taxa known as members of the “Transantarctic Flora” [Wrenn and Beckmann, 1982], but again, the relative abundances in Borehole NBP0602A-3C are quite different as *V. apertura* clearly dominates the assemblage here.

Particularly notable is the occurrence in the uppermost Eocene sampled at 3C (samples 6 and above) of common reworked dinoflagellates of Cretaceous age, such as *Isabelidinium cretaceum*, and various species of the genus *Manumiella*, including *Manumiella seymourensis*. These peridinioid dinoflagellates are the most frequently occurring reworked Cretaceous forms, “after” the abundant acanthomorphs discussed below. Rare specimens of other taxa such as *Odontochitina operculata*, *Palaeocystodinium* sp., and various chorate forms were also noted. Only occasional specimens occur in lower samples.

In samples 5 and above, these reworked Cretaceous dinoflagellate cysts are associated with a major increase in diverse acanthomorph acritarchs such as *Micrhystridium* spp. and occasional *Impletosphaeridium* spp. Most of these forms are darker in color than presumed in-place clear/translucent forms, indicating a thermally more mature status. The thermally mature *Micrhystridium* almost all have a golden hue, compared to the translucent, sometimes almost invisible small forms (more common in lower cores) with definite capitate process tips that are included in the genus *Impletosphaeridium*. The presence of an archeopyle allows for inclusion of some acanthomorph-like forms in the dinocyst *Impletosphaeridium* genus, but an archeopyle is not always easily identifiable. Furthermore, many variations have been observed in the process shape (thinner versus stouter process base, flexible versus straighter process) among the various small acanthomorph forms that we grouped as *Micrhystridium* spp. The higher degree of thermal maturity and the association of these acanthomorph forms with the definite Cretaceous (Campanian-Maastrichtian) dinoflagellate cysts such as *Isabelidinium cretaceum* and *Manumiella seymourensis* in our view confirms that the extremely abundant *Micrhystridium* spp. found in the upper part of NBP0602A-3C are reworked. Askin [1988, 1999] noted that “swarms” or abundant *Micrhystridium* spp. were associated with *I. cretaceum* and the lower range of *M. seymourensis* on Seymour Island. This confirms erosion and redeposition of upper Campanian-lower Maastrichtian rocks in our studied sediments. These Cretaceous forms are found throughout the cored interval, but become abundant in samples 5 and above, indicating that downcutting and erosion is significantly increased at that time.

3.3. Pollen and Spores

Based on the concentration observed and composition (with moderate diversity) of spore and pollen assemblages, the terrestrial palynomorphs indicate that, at the time of deposition for most of the cores, southern beech-dominated vegetation was abundant on the adjacent landmass. It is, however, not always easy to differentiate between penecontemporaneous and recycled origins for much of the assemblage. Some specimens are obviously recycled, as evidenced by their somewhat darker color (higher thermal maturation) and morphologies (e.g., taeniate bisaccate pollen

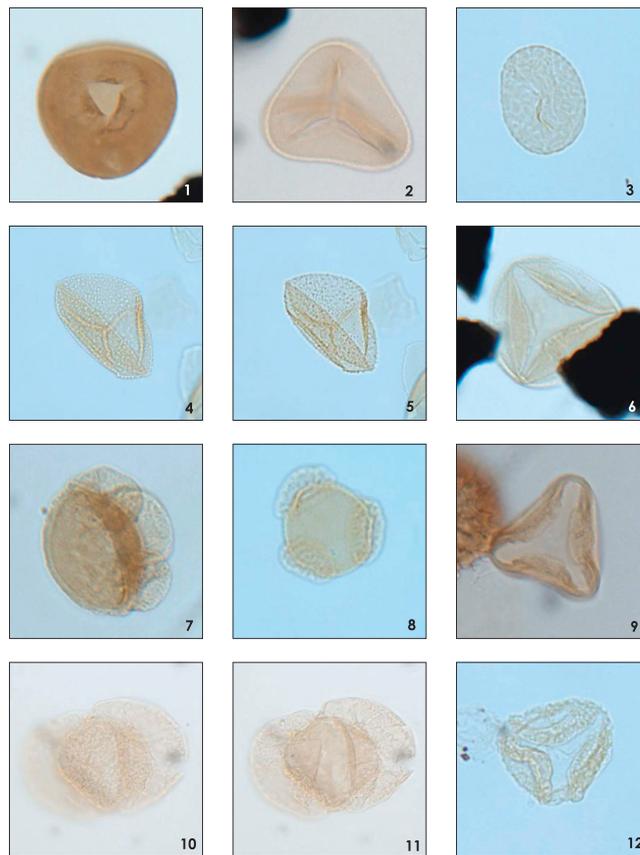


Figure 5. Light photomicrographs of selected species of spore and gymnosperm pollen. For each sample, the sample number (e.g., NBP0602A-3C-1) is followed by the sample depth (e.g., 0.54) and then by the England Finder coordinates of each specimen. Numbers represent the following: 1, unknown spore, NBP0602A-3C-1.54, P33/1; 2, *Cyathidites minor*, NBP0602A-3C-4.85, T43/2; 3, *Coptospora* sp., NBP0602A-3C-6.49, T31/1; 4 and 5, *Osmundacidites wellmanii/Baculatisporites comaumensis* complex, NBP0602A-3C-4.10, R28/2; 6, *Podosporites/Trichotomosulcites* complex, NBP0602A-3C-1.54, U45/3; 7, *Microcachryidites antarcticus*, NBP0602A-3C-1.54, U39/4; 8, *Microcachryidites* cf. *antarcticus*, NBP0602A-3C-7.57, W35/1; 9, *Podosporites/Trichotomosulcites* complex, NBP0602A-3C-4.85, R36/1; 10 and 11, *Podocarpidites* sp., NBP0602A-3C-4.85, Q23/3; and 12, *Podosporites/Trichotomosulcites* complex, NBP0602A-3C-4.10, S33/1.

characteristic of the Permian). For this reason, the designation in Figure 3 for recycled pollen and spores is labeled “Obvious.” Numbers within the recycled group are likely underestimated, however, and the other “in-place” categories likely include recycled specimens that are of similar thermal maturation to the penecontemporaneous flora and have an age range elsewhere that does not with certainty distinguish them as recycled. Some ambiguous occurrences are noted below. Similar problems were encountered in cores recovered from the Ross Sea (e.g., Cape Roberts Project [Raine, 1998; Askin and Raine, 2000; Raine and Askin, 2001]).

Selected spores and gymnosperm pollen are illustrated in Figure 5, and angiosperm pollen are shown in Figure 6. The terrestrial assemblage is conspicuously dominated by pollen of the *Nothofagidites fusca* group, including at least 10 species (some of which may be recycled, as

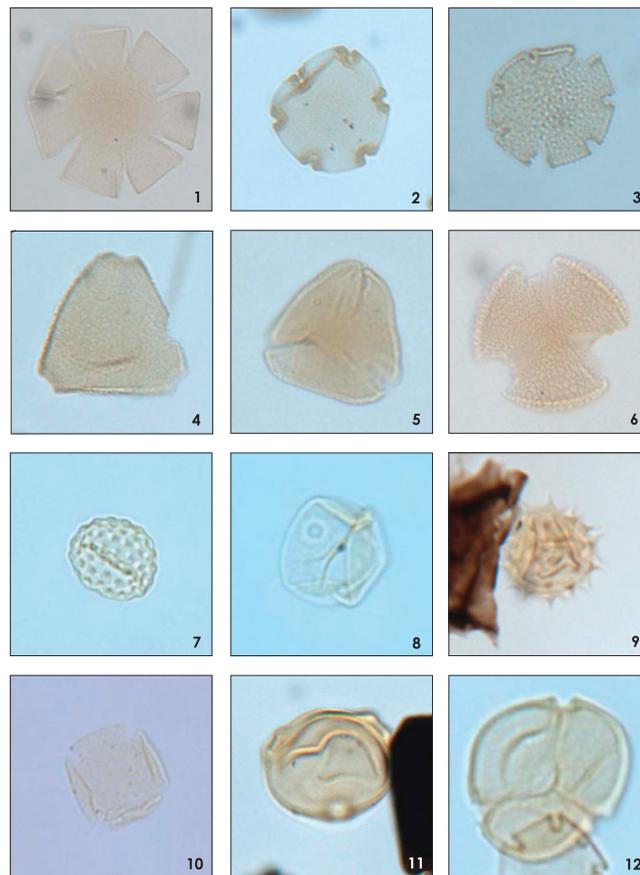


Figure 6. Light photomicrographs of selected species of angiosperms. For each sample, the sample number (e.g., NBP0602A-3C-1) is followed by the sample depth (e.g., 0.54) and then by the England Finder coordinates of each specimen. Numbers represent the following: 1, *Nothofagidites asperus*, NBP0602A-3C-4.85, Q36/2; 2, *Nothofagidites* sp. cf. *N. flemingii*/*N. saraensis* complex, NBP0602A-3C-1.54, V49/4; 3, *Nothofagidites lachlaniae*, NBP0602A-3C-1.54, V30/1; 4, *Proteacidites pseudomoides*, NBP0602A-3C-1.54, R41/1; 5, *Tricolpites ?gillii*, NBP0602A-3C-1.54, U28/3; 6, tricolpate reticulate pollen, NBP0602A-3C-4.85, T25/4; 7, Chenopodiaceae, NBP0602A-3C-2.29, T23/3; 8, Poaceae, NBP0602A-3C-3.59, T41/4; 9, Asteraceae, NBP0602A-3C-1.88, Q43/2; 10, Stylidiaceae, NBP0602A-3C-2.29, R15/3; 11, *Myricipites harrisii*, NBP0602A-3C-1.14, Q46/3; and 12, syncolporate pollen, NBP0602A-3C-3.11, U34/1.

noted above). They include *Nothofagidites lachlaniae*, species similar to (or assignable to) *Nothofagidites waipawaensis* and *Nothofagidites brachyspinulosus* types, the complex of *Nothofagidites flemingii*-cf. *flemingii* (a smaller form, most common of this complex, as in the younger Ross Sea assemblages)- *Nothofagidites saraensis*, and other types such as the moderately large form similar to *N. flemingii* but lacking colpal thickenings and provisionally listed as *N. sp. A* in Ross Sea assemblages. These “*fusca* group” pollen types have similarities to pollen from both the extant *Nothofagus* (southern beech) subgenera *Fuscospora* and *Nothofagus*. There are also scattered occurrences, slightly more common in the lower samples, of *Nothofagidites* spp. *brassii* group (extant beech subgenus *Brassospora*), and *Nothofagidites asperus* (or similar forms, *menziesii* group, extant beech subgenus *Lophozonia*). The overwhelming abundance of *N. fusca* group pollen may be in part related to these pollen being windblown and

produced in huge quantities (also true for podocarp conifer pollen, which are also quite common in the NBP0602A-3C cores), but it is believed that the adjacent vegetation was likely *Nothofagus*-dominated with a high relative diversity of southern beech species. These, and the conifers described below, might have included forest trees to stunted shrubs in more exposed locations and near tree lines.

The second largest grouping within the terrestrial component is the conifer pollen. Almost all of these are podocarp conifer pollen, but there are also a few *Araucariacities australis*, and rare possible Cupressaceae/Taxodiaceae (though similar to some leiosphaerid type algae). The podocarp conifer pollen are quite varied and can mostly be grouped in the bisaccate genera *Podocarpidites* and *Phyllocladidites-Microaladidites* types, with less common but variable pollen of the trisaccate *Podosporites-Trichotomosulcites* type. A few specimens of *Phyllocladidites mawsonii* have been observed, but they may well be recycled (these are common in Cretaceous sediments from the James Ross Basin, as are the trisaccate types), along with *Dacrydiumites* spp. and *Microcachrydites antarcticus*. We note that there are also specimens similar to *P. mawsonii* but without the characteristic boss at the base of each sac and specimens similar to *M. antarcticus* but smaller and with relatively smaller sacs. Even discounting some recycling, there appears to have been a good diversity of podocarp conifers on the adjacent land mass.

Rare Proteaceae pollen are mostly small simple types assignable or similar to *Proteacidites parvus* and *Proteacidites subscabratus*, plus rare occurrences of other species such as *Proteacidites pseudomoides*, *Beaupreaidites* spp. and *Granodiporites* sp. Other angiosperm pollen include rare *Liliacidites*, Restionaceae (monoporate and scrobiculate), and Poaceae (more strongly annulate and smooth, not modern contaminants), various small simple mostly nondescript tricolpate, tricolporate, and triporate pollen, and some larger more distinctive triporate pollen also known from Seymour Island Eocene such as *Myricipites harrisii*, plus rare Caryophyllaceae/Chenopodiaceae types, Ericales, Stylidiaceae, Droseraceae (*Fischeripollis* sp.), and Asteraceae (the latter appear not to be contaminants). Cryptogam spores are rare to infrequent and not very diverse.

The pollen and spores recovered are indicative of a vegetative cover on nearby land similar to that recorded from the La Meseta Formation on Seymour Island, although the SHALDRILL II uppermost Eocene record shows a lower-diversity plant association than that found in the lower and middle La Meseta Formation [Askin, 1997], with *Nothofagidites* spp. *fusca* group clearly dominating the flora and a secondary varied podocarp conifer component. A shift to *fusca*-dominated *Nothofagidites* floras, with concomitant loss of varied *N. brassii* group species occurred in the upper La Meseta Formation [Chen, 2000; R. Askin, unpublished data, 2010]. Unfortunately, a meaningful comparison cannot be made with the uppermost La Meseta assemblage as those sediments were very sandy, and it was believed that small *Nothofagidites* pollen might have been winnowed out with the mud fraction during transport and deposition [Askin, 1997].

There are some similarities to younger Ross Sea Oligocene and Miocene assemblages, including many of the same *Nothofagidites* and podocarp conifer pollen species, and most notably some components of the "tundra assemblage" of ANDRILL-2A [Warny *et al.*, 2009] and the Cape Roberts Project [Askin and Raine, 2000; Raine and Askin, 2001]. These include *Coptospora* spp., Caryophyllaceae/Chenopodiaceae types, Poaceae, Asteraceae, and Stylidiaceae. Although these are only rare occurrences in 3C, it is of interest to note the appearance of these at the end of the Eocene in this area. They are present in the middle and upper cores above sample 16.

Similar aged late Eocene assemblages, though substantially more diverse, especially among Proteaceae, have recently been described from Prydz Bay [Truswell and Macphail, 2009]. Although recycling may account for some of the diversity, these authors instead suggest certain taxa may have survived longer in the cooler East Antarctic environments than in lower-latitude locales such as Australia where their last known occurrences do not extend into the Eocene. For

these late Eocene Prydz Bay floras, a mosaic vegetation of dwarfed (krumholtz) trees, scleromorphic shrubs, and wetland herbs, analogous to the present northern taiga, was suggested [Truswell and Macphail, 2009]. The Eocene Proteaceae on the Antarctic Peninsula were apparently much less diverse and suggest the scleromorphic component of the flora might be lacking. This is consistent with a much higher rainfall/higher humidity climate in the Eocene Antarctic Peninsula, (similar to present-day southern Chile and southwestern New Zealand), as might be expected in the more maritime peninsula conditions, compared to coastal East Antarctica. The taiga-like vegetation of dwarfed trees envisaged for the similar aged Prydz Bay floras is a good analogy for the interval represented by the middle and upper NBP0602A-3C cores, with tundra developing on the higher and more exposed parts of the landscape.

In addition to in situ pollen and spores, recycled Cretaceous forms (e.g., *Cicatricosisporites australiensis*), many with a darker hue and battered and corroded so that many are unidentifiable to species level, are found scattered throughout the cores. They become substantially more common in the uppermost section, starting at sample 5. A similar trend is observed with the marine palynomorphs.

Permian-Triassic recycled specimens are found sporadically throughout the core, though are somewhat more common in the lower samples. Permian-Triassic pollen and spores occur throughout the Seymour Island succession as well but are noticeably more common in the upper La Meseta Formation [Askin and Elliot, 1982], a further similarity to the lower NBP0602A-3C cores. Like the La Meseta recycled specimens, those found throughout 3C mostly exhibit relatively low thermal maturation with their yellow-orange to orange-brown coloration, compared to brown-black Permian palynomorphs found in place in the Transantarctic Mountains. Relatively unaltered emergent forearc sediments adjacent to the Antarctic Peninsula were suggested as a possible source for the recycled palynomorphs by Askin and Elliot [1982].

4. DISCUSSION

4.1. Biostratigraphy and Global Implications of the Age Model

Stratigraphic inferences for Hole NBP0602A-3C are mainly based on a combination of seismic profiles tied to diatom and nannofossil biostratigraphy. These biostratigraphic data are presented in the SHALDRIL II shipboard report (Shipboard Scientific Party, 2006) and are summarized by Bohaty *et al.* [this volume]. Although dinoflagellate cysts, as yet, are only of limited use in Antarctic Neogene biostratigraphic studies, some promising work has been published recently for some Oligocene-Neogene sections [Hannah *et al.*, 2000, 2001a, 2001b] showing that dinoflagellate cysts are good stratigraphic markers for Cretaceous to Eocene Antarctic sections [e.g., Wrenn and Hart, 1988; Hall, 1977]. The dinoflagellate cyst biostratigraphic model in this study allows us to narrow the age of the drilled section. Based on the presence of the diatoms *Rhizosolenia oligocaenica* and *Rylandsia inaequiradiata* [Bohaty *et al.*, this volume], the age of the section was estimated to range anywhere between 32 and 37 Ma. Based on known distributions of key dinoflagellate cysts present in the NBP0602A-3C borehole, mainly the last occurrence datum of *Spinidinium macmurdoense* and *Vozzhennikovia rotunda*, this window can be narrowed to 33.7 to 37 Ma [Bohaty *et al.*, this volume]. This age is based on dinoflagellate cyst ranges summarized by Williams *et al.* [2003], based on their review of literature and new data from Ocean Drilling Program Leg 189 in the Tasmanian seaways. This biostratigraphic interpretation is further supported by the 35.9 Ma strontium date obtained at the base of core NBP0602A-3C-5 [Bohaty *et al.*, this volume]. These combined stratigraphic data confirm that Borehole NBP0602A-3C sampled the Priabonian.

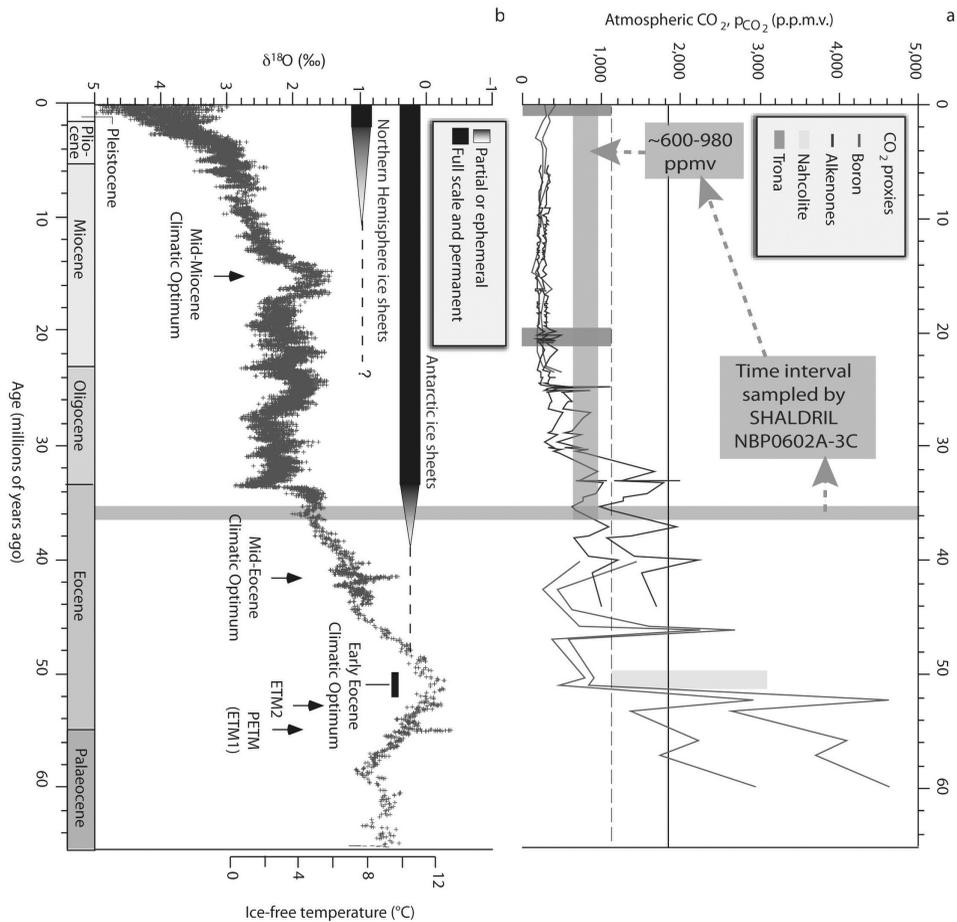


Figure 7. Stratigraphic position of sediment recovered from the NBP0602A-3C borehole in relation to the atmospheric CO₂ levels and global climate. The horizontal shaded zone represents the maximum interval of time sampled by NBP0602A-3C (this is the maximum range possible based on the biostratigraphy available for the well). The central vertical shaded zone projects the width of the atmospheric CO₂ curve at the time sampled by NBP0602A-3C on the atmospheric CO₂ axis to give a minimum and maximum range of atmospheric CO₂ value at the time of deposition. Modified from *Zachos et al.* [2008]. Reprinted by permission from Macmillan Publishers Ltd: *Nature*, copyright 2008 (<http://www.nature.com/nature/index.html>).

Comparison with the atmospheric CO₂ levels and oxygen isotope proxy curve presented in the *Zachos et al.* [2008] summary (Figure 7) indicates that NBP0602A-3C recovered a key stratigraphic interval in the Priabonian. Although the sedimentary layers sampled cannot be more precisely dated than being deposited sometime between 37 and 33.7 Ma, it can be inferred that the palynological record from this interval captured the response of plants and organic-walled phytoplankton during the first marked increase in δ¹⁸O in the latest Eocene, followed by a large reduction in atmospheric CO₂. This event directly precedes the major Oi-1 glaciation that marks the Eocene/Oligocene boundary. During the interval sampled by SHALDRIL II, the atmospheric CO₂ could have been as low as 600 ppmv but up to 980 ppmv depending on the various CO₂

proxies presented by *Zachos et al.* [2008]. To put these values into the context of modern climate debates, the concentration of carbon dioxide in the atmosphere (based on data available on the NASA Web site) at the start of the industrial revolution was about 280 ppmv; it then rose to 300 ppmv by the late 1940s, reaching today's concentration of 360 ppmv. At these current rates, the atmospheric CO₂ is expected to reach 560 ppmv, within the next 100 years. If the minimum values of atmospheric CO₂ presented in the *Zachos et al.* [2008] summary represent the environmental atmospheric concentration at time of NBP0602A-3C deposition, this means that the system and vegetative cover represented by the NBP0602A-3C cored interval might reflect what can be expected for the next century.

4.2. Discussion on Ecology and Assemblage Composition

Overall, the low-diversity/high-dominance dinoflagellate cyst assemblage is clearly a sign of deteriorating conditions compared to those observed in most of the Eocene section sampled on Seymour Island. In the NBP0602A-3C section, the majority of species present throughout the interval are peridinioid species (*Vozzhennikovia* spp., *Deflandrea* spp., *Spinidinium* spp.). If these species are indeed heterotrophic, as is the case for many modern peridinioids, then their dominance suggests that surface waters were eutrophic at the time these algae lived. This could indicate an environment such as an upwelling zone or a deltaic complex. Most of these dinoflagellate cysts are common in the Transantarctic Flora as described by *Wrenn and Hart* [1988], but the high relative abundance in *V. apertura*, a thicker, possibly more robust dinoflagellate cyst, might also illustrate the fact that the environment has a higher energy, possibly as a result of the general shallowing of the section, though other lines of evidence are lacking for this hypothesis. It is more likely that the low-diversity/high-dominance assemblage signifies significantly colder surface waters compared to the environments known from the Seymour Island Eocene sections.

Throughout the interval, both marine and terrestrial species recovered indicate cold climatic conditions. For the lower cores, the vegetation might have grown in climatic conditions similar to those found in the colder forested parts below tree line of southern Chile and southwestern New Zealand today and somewhat harsher than those suggested for the middle Eocene of Seymour Island. *Francis et al.* [2008, and references therein], based on analysis of leaves, suggested a markedly seasonal climate for the middle Eocene of this region with a mean annual temperature of $10.8^{\circ}\text{C} \pm 1.1^{\circ}\text{C}$, a warm month mean of $24^{\circ}\text{C} \pm 2.7^{\circ}\text{C}$, a cold month mean of $-1.17^{\circ}\text{C} \pm 2.7^{\circ}\text{C}$, and 1534 mm annual rainfall.

Environmental conditions both on land and in the marine realm seem to have taken a turn for the worse between the deposition of samples 16 to 15. At that level, the high concentration in palynomorphs observed in the lower cores (samples 16 through 20) dropped by 85% for marine palynomorphs and by 90% for terrestrial palynomorphs and remained low in the rest of the cored interval. The change in concentration is also paralleled by relative abundance increases in pollen of conifers and the dinoflagellate cyst *V. apertura*. But this drop may be a reflection, at least in part, of sudden decrease in marine and terrestrial palynomorph productivity, although changes such as an increased sedimentation rate cannot be ruled out. However, no obvious changes in the lithology were reported between samples 16 and 15 where the concentration drop is observed, so a possible change in sedimentation conditions and possibly provenance are not well supported. Furthermore, one would expect that the important increase in terrigenous input indicative of higher sedimentation rate might be associated with input of reworked palynomorphs into the assemblage, but such an increase is not observed in sample 15. Thus, the lower-productivity hypothesis is favored over the increased sedimentation rate. *Diester-Haass and Zachos* [2003] evaluated the change in paleoproductivity during the Eocene-Oligocene transition. Their record indicates a prominent

increase in productivity in the Southern Ocean. They postulated that this widespread increase may have led to enhanced carbon burial that contributed to CO₂ extraction, hence acting as positive feedback to the already cooling climate. Increases in productivity are not seen in any of our younger Eocene samples. This suggests that the increased productivity discussed by Diester-Haass and Zachos was not the result of vegetation or organic-wall plankton proliferation, but most likely, a consequence of blooms in siliceous-walled microfossil microplankton such as radiolarians or diatoms, which we know thrive today in polar and subpolar conditions in response to abundance in food and silica content in polar and subpolar ocean waters.

Considering this drastic decrease in concentration in sample 15 and above, it does appear that conditions changed simultaneously on land and in the ocean, as there is no discernible lag in major assemblage composition when marine and terrestrial assemblages are compared. Further detailed species by species comparisons in both marine and terrestrial assemblages will be needed to confirm this initial interpretation. The concentrations in palynomorphs keep decreasing substantially toward the middle of the section, possibly linked to further deteriorating conditions, and decrease even more at the top of the section. Unlike elsewhere in the section, this upper decrease is coincident with a significant increase in reworked palynomorphs. This major change may record a more significant sea level drop, induced by substantial cooling and development of glaciers. Based on the age of the majority of the reworked palynomorphs, the reworked marine and terrestrial forms were likely incorporated in the sediment during downcutting and redeposition of nearby Campanian-Maastrichtian sections at the end of the Eocene.

Oxygen isotopic values for the time interval recovered by SHALDRIL indicate an increasing trend. Based on the oxygen isotope record alone, it cannot be distinguished if these are characteristics of increased ice volume, decreasing temperature, or both. On the basis of the SHALDRIL NBP0602A-3C palynological record, a two-step cooling is suggested. We propose that during the first step, cooling caused the drop in productivity and thus concentration in the preserved palynomorph assemblage between samples 16 and 15. The second cooling step occurred between samples 6 and 5 and is marked by greatly increased reworking activity, hence indicating a drop in sea level most likely related to ice sheet expansion. This downcutting event is unfortunately not dated with great precision, although evidence shows it occurred between 33.7 and 35.9 Ma. During this time interval, around 35.5 Ma, a marked decrease in temperature is seen in the oxygen isotope curve and in the TEX₈₆ results of DSDP Site 511 off Argentina [Liu *et al.*, 2009]. For that time interval, both the oxygen isotopes and the TEX₈₆ method indicate a drop in temperature of 6°C to 7°C. Although these methods cannot indicate the presence of an ice sheet, this cooling event might be correlated to the major sea level drop we report between samples 6 and 5. Interestingly, the replacement of prodeltaic endemic Antarctic dinoflagellate cyst assemblages by open marine cosmopolitan communities at three Ocean Drilling Program Leg 189 sites (1170, 1171, and 1172) indicates that the deepening of the Tasmanian Gateway was quasi-synchronous throughout the Tasmanian region and that it started at ~35.5 Ma [Sluijs *et al.*, 2003].

The second cooling event that we report between the deposition of cores NBP0602A-3C-3 (sample 6) and NBP0602A-3C-2 (sample 5) appears to be associated with ice sheet expansion and is dated between 35.9 and 33.7 Ma. Although the palynological changes indicative of sea level drop observed between samples 6 and 5 are abrupt, it is possible that these changes actually happened gradually. Stratigraphic data do not have the resolution needed to identify whether the sequence is continuous or if a minor hiatus marks this level. Actually, a noticeable change in sediment coloration, from dark greenish gray for samples 6 and below to greenish black for samples 5 and above [Anderson *et al.*, 2006], might indicate that such a hiatus indeed exists between samples 6 and 5.

From the NBP0602A-3C record, we see that both dinoflagellate assemblages and the vegetation indicate cooler climatic conditions sometime between 35.9 and 33.7 Ma. Without more precise

stratigraphic resolution, it is not possible to determine whether the changes we see in the Weddell Sea occurred concurrently with the 35.5 Ma deepening of the Tasmanian Gateway, but we argue that the lowering of atmospheric CO₂ concentration must have played the predominant role for the cooling trend seen prior to 35.5 Ma.

5. CONCLUSIONS

Significant global decrease in diversity of organic-walled phytoplankton and in vegetation had already occurred by the end of the Eocene, at least by 36 Ma, hence at least 2.3 Myr before the sharp marine oxygen isotope ratio shift that reflects marked global cooling at the Eocene-Oligocene boundary and before the 35.5 Ma deepening of the Tasmanian Gateway. This is clearly indicated by the low diversity/high abundance in a few species of dinoflagellate cysts such as *V. apertura*, *S. macmurdoense*, and *D. antarctica* and in the dominance, among the vegetation, of pollen of *Nothofagidites* spp. *fusca* group with secondary podocarp conifers.

Following this cooling phase, a second, possibly more intense cooling took place in the upper part of the section. In these upper samples, in addition to extremely low concentration of in situ palynomorphs, a significant increase in reworking activity is clearly obvious. The abundance in the acritarch *Micrhystridium* spp. along with significant increase in reworked Cretaceous dinoflagellate cysts, pollen, and spores at that level is considered to represent a period of intense erosion of nearby upper Campanian–lower Maastrichtian sections. This downcutting was most likely induced by a marked sea level drop, probably associated with growth of ice sheets in and off Antarctica. This may be correlated to what is interpreted in the seismic profile as a major onlap surface, which *Smith and Anderson* [this volume] argued represents a significant low-stand. It is possible (D. H. Elliot, personal communication, 2010) that this surface corresponds to the erosion surface on top of the meseta on Seymour Island, between the La Meseta Formation and the overlying ?Eocene/Oligocene glacial beds described by *Ivany et al.* [2006]. A possible relationship is also suggested to some of the valley glaciers that are reported from King George Island around that time [*Francis et al.*, 2009; J. B. Anderson, personal communication, 2010].

Based on biostratigraphy and the 35.9 Ma strontium date obtained at the base of core NBP0602A-3C-5, it is postulated that the drop in concentration in the lower part of the core and major lowering of sea level in the upper part of the core are most likely related to the brief spike in $\delta^{18}\text{O}$ -enriched value observed from 36 to 35.5 Ma in the *Zachos et al.* [2001, 2008] composite record. If this date is correct, the section recovered by SHALDRIL gives us a glimpse into what the world might look like once carbon dioxide concentrations in the atmosphere reach a level two to three times our current value.

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