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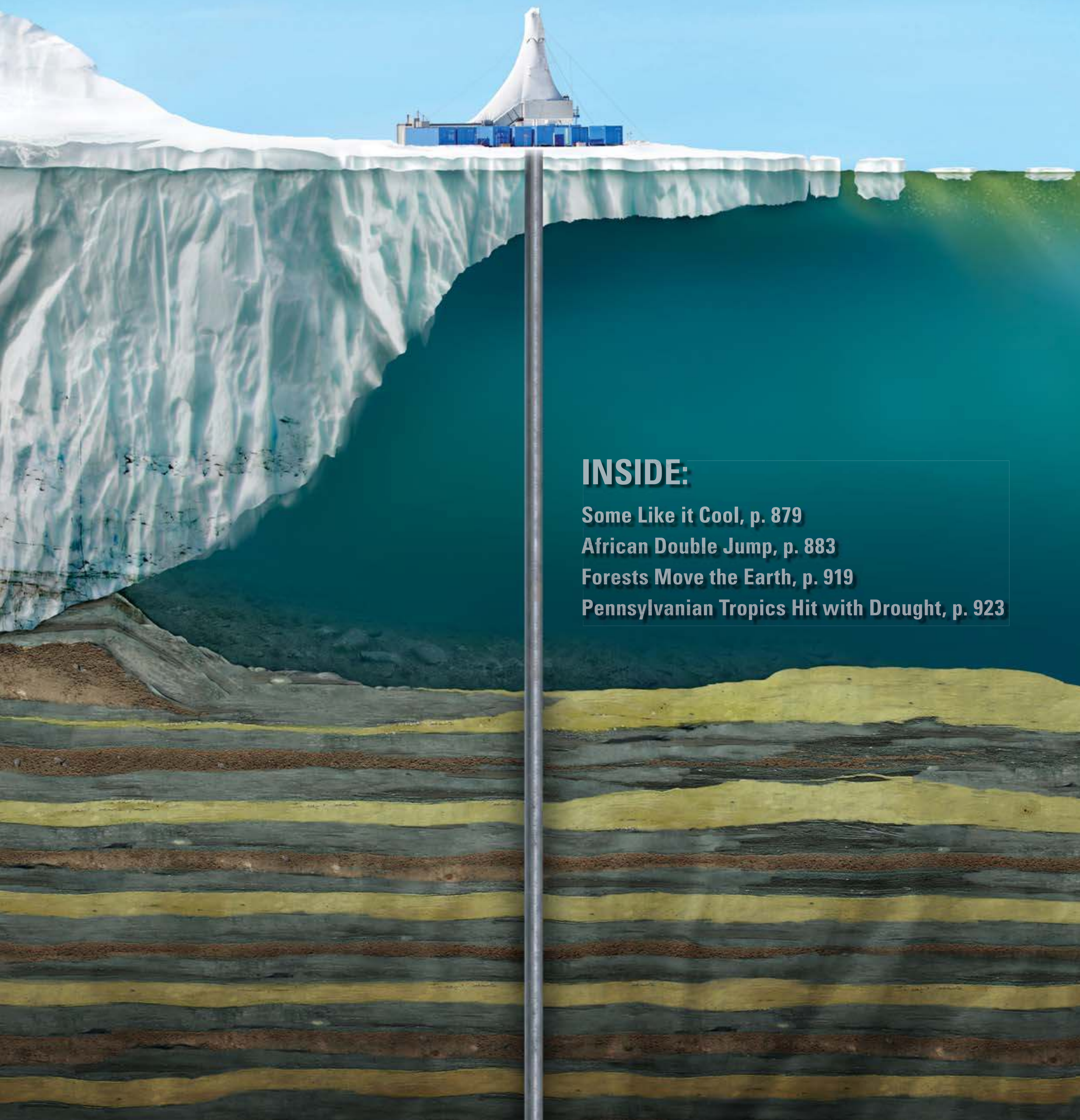

## INSIDE:

# Palynomorphs from a sediment core reveal a sudden remarkably warm Antarctica during the middle Miocene

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## ABSTRACT

**An exceptional triple palynological signal (unusually high abundance of marine, freshwater, and terrestrial palynomorphs) recovered from a core collected during the 2007 ANDRILL (Antarctic geologic drilling program) campaign in the Ross Sea, Antarctica, provides constraints for the Middle Miocene Climatic Optimum. Compared to elsewhere in the core, this signal comprises a 2000-fold increase in two species of dinoflagellate cysts, a synchronous five-fold increase in freshwater algae, and up to an 80-fold increase in terrestrial pollen, including a proliferation of woody plants. Together, these shifts in the palynological assemblages ca. 15.7 Ma ago represent a relatively short period of time during which Antarctica became abruptly much warmer. Land temperatures reached 10 °C (January mean), estimated annual sea-surface temperatures ranged from 0 to 11.5 °C, and increased freshwater input lowered the salinity during a short period of sea-ice reduction.**

## INTRODUCTION

Given current climate concerns, finding a direct ice-proximal record of the climate during the Middle Miocene Climatic Optimum (MMCO) in Antarctica is crucial to allow modelers to project better how the ice sheet might respond to future global warming. Geochemical evidence from deep-sea proxy records indicates that the climate during the MMCO was significantly warmer than today (Lear et al., 2000; Zachos et al., 2001), but until ANDRILL (Antarctic geologic drilling program; Florindo et al., 2008; Harwood et al., 2009), a complete proximal record of the MMCO had never been successfully sampled in Antarctica. In the austral summer of 2007, a 1138.54 m core was drilled from a sea-ice platform in southern McMurdo Sound (77°45.488′S; 165°16.613′E). Deposits are characterized by lithological changes reflecting variations in sea level, glacial proximity, and climate (Florindo et al., 2008; Harwood et al., 2009). Biostratigraphy, magnetostratigraphy, and radiometric dating (Acton et al., 2009) suggest that the ANDRILL AND-2A (Fig. 1) core comprised a thick lower and middle Miocene section disconformably overlain at 224.82 m below seafloor (mbsf) by a condensed upper Miocene to Holocene section. This paper discusses palynomorphs recovered from the lower to middle Miocene interval dated as 17.20–12.46 Ma old (Acton et al., 2009).

## METHOD

Detailed palynological analyses of the core were undertaken for reconstruction of paleoclimate from paleovegetation (spore and pollen analysis) and sea-surface conditions (fossil dinoflagellate cyst and acritarch analysis). The science team at McMurdo Station (Antarctica) collected 230 palynological samples between the depth of 28.28 and 1107.7 mbsf at ~5 m intervals. Alternate samples were sent for processing to the United States (Warny and Askin), to New Zealand (Hannah and Raine), and to Germany (Mohr). Laboratories used a similar standard processing method, involving successive treatment of 10–20 g of dry sample with hydrochloric acid, hydrofluoric acid, and some or all of the following: nitric acid, heavy liquid flotation, and sieving to retain the 6–250 µm size fraction (Brown, 2008). Consistency between laboratories was cross-checked by triple splitting a larger sized sample to ensure that sample residues obtained in these laboratories were comparable. The New Zealand and United States residues were stained with Safranin red dye. All 230 samples were processed and

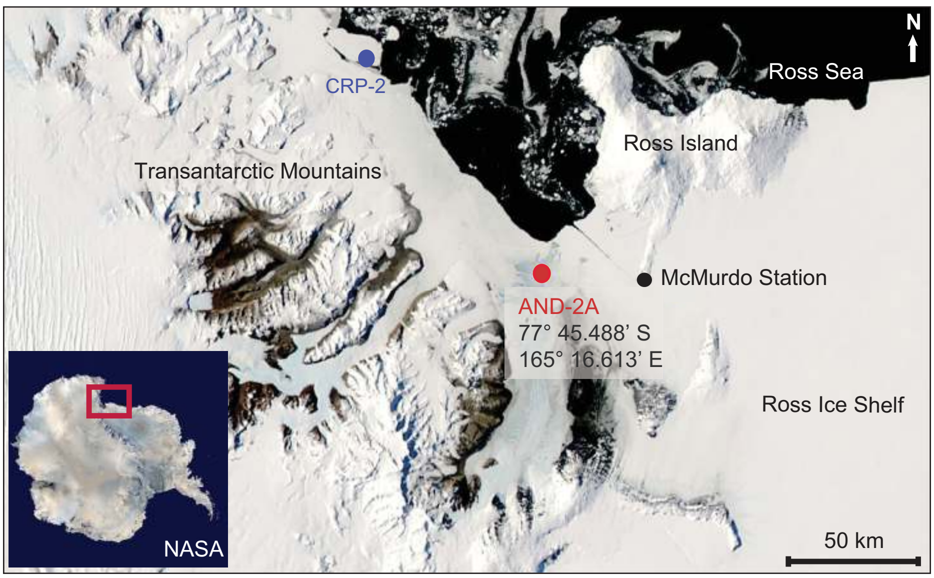


**Figure 1. Location of AND-2A drillhole in southern McMurdo Sound, western Ross Sea, Antarctica.**

*Southern McMurdo Sound Project: http://andrill.org/projects/sms/team.html.

preliminary taxonomic and quantitative palynological analyses were performed. All samples yielded both marine and terrestrial palynomorphs, with varying absolute abundance and diversity. A series of evenly distributed samples was fully tabulated. We discuss details of 93 samples in this paper. These include a second higher-resolution series of 15 samples (20 cm spacing) taken in the interval deemed palynologically exceptional. These were processed by a single laboratory, and the residue slides were shared and analyzed by all palynologists (Fig. 2; see the GSA Data Repository[1] for a complete list of data).

## RESULTS AND DISCUSSION

The palynological analysis identified a unique 2-m-thick layer between 312 and 310 mbsf that yielded abundant palynomorphs, with a dinoflagellate cyst content that vastly exceeds numbers recorded in other Antarctic cores of Neogene age (Hannah et al., 1998, 2000; Wrenn et al., 1998; Warny et al., 2006). This layer is a diatomite (shown in yellow in Fig. 2), and is the only such layer in the core, suggesting optimal conditions for diatoms. The exceptional concentration of palynomorphs was confirmed by the high-resolution sampling, and fossil dinoflagellate cysts, freshwater algae, and pollen and spores all indicate an extraordinary set of environmental conditions during the time represented by this 2 m interval.

### Marine Palynomorphs

Sparse to moderate assemblages of presumed penecontemporaneous marine palynomorphs, including occasional dinoflagellate cysts and common leiospheres, plus reworked Eocene taxa such as *Vozzhennikovia apertura*, were recovered throughout the drillhole. Unlike previously described Antarctic Neogene or Holocene assemblages (Harland et al., 1998; Harland and Pudsey, 1999; Hannah et al., 2000; Marret and de Vernal, 1997; Troedson and Riding, 2002; Warny et al., 2006), the marine palynomorphs recovered between 312 and 310 mbsf exhibit high abundance in two species of dinoflagellate cysts, *Operculodinium centrocarpum* (Deflandre and Cookson) Wall 1967 (a 500-fold increase) and *Pyxidinopsis braboi* (de Schepper et al., 2004) (an almost 2000-fold increase). This sudden productivity peak may record significant ice retreat during a short warm interval. Because these species are absent or rare in most of the core, the high productivity recorded between 312 and 310 mbsf, with two smaller peaks at 431.91 and 294.5 mbsf, may indicate that they were able to migrate to the area from a refuge (probably north of lat 60°S, based on a study by Harland et al.,1998). *O. centrocarpum* is a cosmopolitan species recorded from many Neogene sections worldwide in cool, temperate, or warm regions (e.g., Edwards and Andrle, 1992; Harland et al., 1998; Warny et al., 2003). Although considered tolerant of a diverse set of environmental conditions, *O. centrocarpum* is rare or absent in Neogene sediments sampled at latitudes higher than 60°S (Harland et al., 1998). Marret and Zonneveld (2003) recorded *O. centrocarpum* as composing only a small part of the dinoflagellate cyst assemblages documented from south of the Antarctic subpolar front, and found the highest relative abundances in the northern North Atlantic Ocean and the Benguela Current regions. They concluded that the species is distributed within a broad range of environmental conditions, with sea-surface temperature (SST) ranging from −2.1 to 29.6 °C, sea-surface salinity ranging from 16.1 to 36.8, and with various phosphate (0.1 and 1.7 μM) or nitrate (0 and 22.8 μM) levels. In contrast, *O. israelianum* is also widespread but prefers warmer conditions, and in tropical areas it often outpaces *O. centrocarpum* in abundance. *O. israelianum* is found in regions with SST ranging from 11.5 °C in the winter to 29.2 °C in the summer (Marret and Zonneveld, 2003). The presence of *O. centrocarpum* together with the absence of *O. israelianum* in the AND-2A drillcore samples suggest that the SST range for the Ross Sea was probably restricted to −2.1 to 11.5 °C during peak intervals of the MMCO.

The other co-dominant species, *P. braboi*, has been described from Pliocene deposits in the Antwerp area of Belgium (de Schepper et al., 2004). The age of the type locality for this species is early to late Pliocene (Louwye et al., 2004), and the assemblage reflects a neritic depositional environment along the southern margin of the North Sea Basin in a temperate to cool climate, before the onset of significant Northern Hemisphere cooling ca. 2.6 Ma ago. Other than the type locality, *P. braboi* has been recorded only from two additional sites; this study, and in Oligocene strata sampled by the Cape Roberts drillhole CRP-2/2A, in the Victoria Land Basin, Antarctica. In the CRP-2/2A drillhole, *P. braboi* only occurred in the lower to middle Oligocene interval, which was thought to have been warmer than the lower Miocene section higher in the core (Hannah et al., 2000).

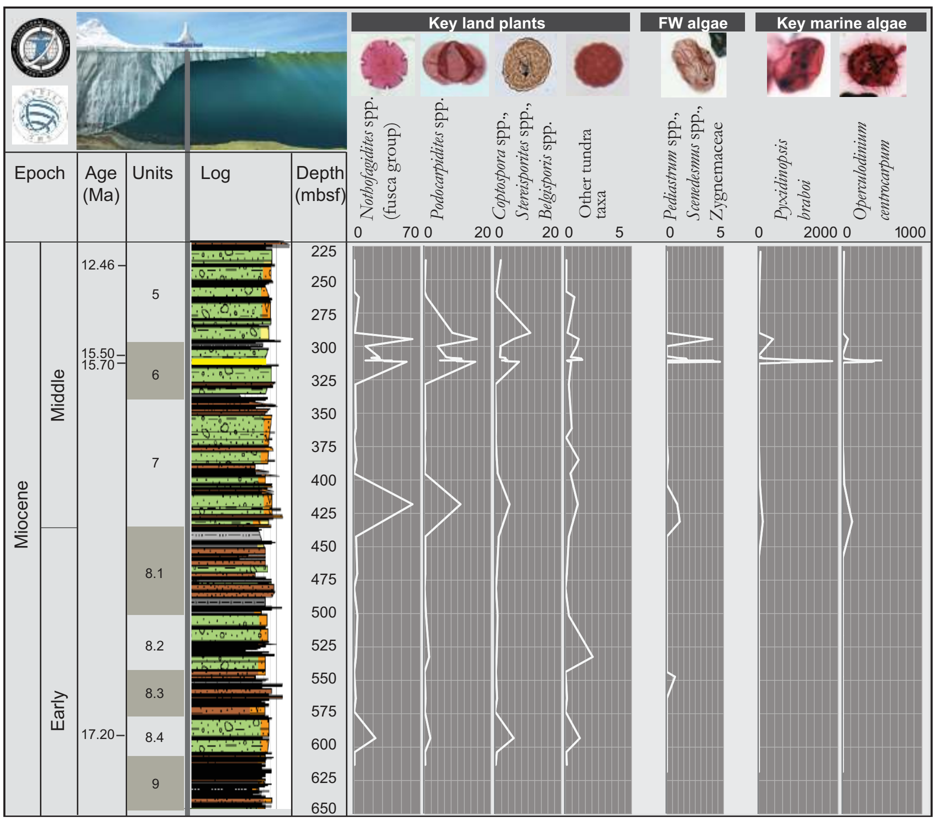


**Figure 2. Concentration in palynomorphs per gram of dry sediment in relationship to core depth, lithology (bright yellow layer is diatomite), and age. FW—freshwater algae; mbsf—meters below seafloor. Note: plots are independently scaled.**

[1]GSA Data Repository item 2009235, table presenting the concentration in key palynomorphs per gram of dry sediment, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

In general, gonyaulacoid dinoflagellates such as these are autotrophic and thrive when light allows photosynthesis to occur. Sea ice is a major limiting factor preventing dinoflagellate growth along the Antarctic coast today, and probably explains the paucity of dinoflagellate cysts in post-Eocene Antarctic sediments (Warny et al., 2006). Therefore, the major occurrences of *Operculodinium* and *Pyxidinopsis* suggest that conditions were locally ice free during the key interval studied. Salinity fluctuations may have played a major role in limiting the dinoflagellate cyst assemblage to essentially two species. Indeed, *O. centrocarpum* is one of the few dinoflagellates tolerant of substantial salinity fluctuations. Dale (1996) showed that *O. centrocarpum* is one of only two dinoflagellate cyst species that persisted through the full range of salinities, even overlapping with the distribution of freshwater algae.

**Freshwater Algae**

Spores of green algae Zygnemaceae and colonial chlorococcales *Pediastrum* and *Scenedesmus*-type algae are all notably more abundant in the samples that record high abundances in dinocyst, pollen, and spores than elsewhere in the core. The freshwater algae Zygnemaceae are often found in shallow, stagnant waters where they can easily be observed as a green surface layer at the margins of lakes, in flowing water, and in moist soils (van Geel and Grenfell, 1996). Zygnemaceae have no marine representatives, and similarly, *Pediastrum* and *Scenedesmus* are found today in freshwater habitats (Batten, 1996). The presence of these algae in the AND-2A drillcore sediments suggests an increase in temperature and meltwater (and possibly rainfall) producing ponds and lakes adjacent to the Ross Sea. The peak in the numbers of freshwater algae between 312 and 294 mbsf (fivefold increase, Fig. 2) also implies a significant amount of freshwater runoff into the Ross Sea, supporting the suggestion that salinity levels may have controlled the low-diversity dinocyst assemblages.

**Terrestrial Palynomorphs**

The key trend in the spore and pollen record is the absolute and relative abundance increases in *Podocarpidites* (podocarp conifer, up to 16-fold increase) and *Nothofagidites* pollen (southern beech, more than 60-fold increase) in samples from 312 to 284 mbsf. The peaks indicate proliferation of these woody plants, possibly also with increased stature to more tree-like form from their typical Antarctic Neogene prostrate to low shrubby habit. We suggest a comparison to the recently reported expansion of boreal coniferous forest in southern Greenland during the Pleistocene, when pollen records indicate expansion of spruce forest concomitant with extensive deglaciation during Marine Isotope Stage 11 (de Vernal and Hillaire-Marcel, 2008; Steig and Wolfe, 2008). An earlier pollen peak at 418 mbsf is not coincident with large increases in concentration of freshwater algae and dinoflagellate cysts. Peaks in abundance are also observed in other components of the vegetation, including bryophytes (mainly *Coptospora* spp., moss, possibly Bartramiaceae), a *Lycopodium* (clubmoss) similar to an extant Patagonian species, and angiosperms characteristic of modern subantarctic and austral-alpine environments (grouped in Fig. 2 as "other tundra taxa") such as Caryophyllaceae (*Colobanthus* type, pearlwort), Stylidiaceae (trigger plants), Droseraceae (sundews), Campanulaceae (bellflowers), Ericales (heaths), Poaceae (grasses), and Typhaceae and/or Sparganiaceae (bullrushes, burr reeds). Some taxa were previously recorded from the latest Oligocene to early Miocene CIROS-1 (Mildenhall, 1989) and Cape Roberts Project cores (Raine, 1998; Askin and Raine, 2000; Raine and Askin, 2001; Prebble et al., 2006), and from Sirius Group outcrops at the Beardmore Glacier and Dry Valleys (Askin and Markgraf, 1986; Prebble et al., 2006; Ashworth et al., 2007), while others are new records from the Ross Sea region. Absolute and relative abundances of *Coptospora* and other tundra plants stay high after the woody plants fade from the record above the diatomite and above the 418 mbsf peak, suggesting that tundra components occupied open ground before ice again encroached. The spore-pollen assemblages represent mossy tundra vegetation with shrubby podocarps and *Nothofagus*, and other plants varying according to topographic aspect and microclimate (Fig. 3). For most of the early and middle Miocene interval, a general climate cooler than the modern austral polar-alpine tree limit (~10 °C January mean) is suggested, but the abnormally high concentrations of *Nothofagidites* and *Podocarpidites* pollen recovered at 418 and 312–284 mbsf may represent times when 10 °C January mean temperatures were reached and possibly exceeded.

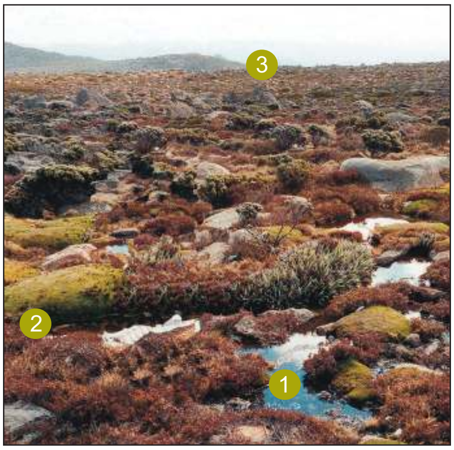


**Figure 3. View of what Antarctica possibly looked like during Middle Miocene Climatic Optimum, based on palynological fossil data. Freshwater algae flourished in meltwater ponds (1), low tundra vegetation grew on the coastal plain (2), while a mosaic of tundra with shrub-like southern beech and low podocarp trees (3) grew on warmer sites. Tallest shrubs are ~50 cm in height.**

**Other Supporting Evidence**

Evidence for extensive middle Miocene subglacial floods and freshwater discharge predating 12.4 Ma were reported from the Labyrinth, a series of channels and canyons incised into a 300-m-thick sill of Ferrar Dolerite at the head of Wright Valley (Lewis et al., 2006). These channels are believed to be consistent with fast-flowing subglacial meltwater discharging large volumes of freshwater into the Ross Sea during the middle Miocene. Glacial records from the Transantarctic Mountains also indicate that glaciers underwent extensive basal and surface melting prior to 13.94 Ma ago during climatic conditions warmer than today (Lewis et al., 2007).

**CONCLUSIONS**

Preliminary dating of the AND-2A core via magnetostratigraphy, isotope stratigraphy, and biostratigraphy (Acton et al., 2009) places the peak of the 312–310 mbsf warm interval ca. 15.7–15.5 Ma ago. Other warming events documented by high abundances in pollen and spores in the base of unit 7 and above the diatomite were apparently less intense, as indicated by the smaller increase in dinoflagellate cyst concentrations. In contrast, the remarkable dinoflagellate cyst concentrations documented between 312 and 310 mbsf suggest that climatic warming reached a peak ca. 15.7 Ma ago, when SSTs ranged from 0 to 11.5 °C. During this relatively short-lived peak in temperature, terrestrial palynomorphs suggest that mean January (austral summer) temperatures reached at least 10 °C. The simultaneous peak in freshwater algae implies significant release of fresh meltwater to the Ross Sea region. These climate fluctuations probably reflect a poleward shift of the jet stream in the Southern Hemisphere, pushing warmer water toward the pole, allowing a few dinoflagellate species to flourish in ice-free conditions and woody plants to proliferate in warmer continental temperatures. This singular major warming peak seen in the palynological record occurred during a longer interval of warming (MMCO), as indicated by the other peaks in pollen abundances. The peak warming (seen in the triple palynological signal of plants, freshwater algae, and plankton) apparently lasted a relatively short time, and is very similar in terms of abruptness and intensity to the warming event (Kennett and Stott, 1991; Sluijs et al., 2007) that occurred at the end of the Paleocene.

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