

# Changing Oligocene climate recorded by palynomorphs from two glacio-eustatic sedimentary cycles, Cape Roberts Project, Victoria Land Basin, Antarctica

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## Abstract

Two marine palynomorph assemblages recovered from two glacio-eustatic sedimentary cycles from the Cape Roberts Project (CRP), which recovered over 1500 m of Oligocene and Miocene strata from the western margin of the Victoria Land Basin, are investigated. We present results from one cycle dated as early Oligocene and the other dated as late Oligocene. Modest numbers of marine palynomorphs were recovered, with an average abundance of 56 specimens per gram. The assemblages recovered from both cycles are broadly similar, and dominated by acritarchs and the phycoma of prasinophyte algae. These include *Leiosphaeridia* sp. 2, *Leiosphaeridia* sp. 3, and the prasinophyte alga, *Cymatiosphaera* sp. 2. In detail, however, the lower Oligocene assemblage is different from that of the upper Oligocene. The lower Oligocene cycle includes *Impagidinium* cf. *dispartium* and *Impagidinium* cf. *elegans*. *Cymatiosphaera* sp. 6 and *Pyxidinospis* sp. are abundant. The upper Oligocene cycle is characterized by an absence of *Cymatiosphaera* (?) *invaginata*, *Cymatiosphaera* sp. 8, and *Pterospermella* sp. A. It has very low numbers of *Acritarch* sp. b, *Impagidinium* and *Pyxidinospis*. It contains *Tasmanites* sp. and *Brigantedinium pynei*, and it has higher abundances of *Lejeunecysta* sp. 1 and *Sigmopollis* than the lower Oligocene cycle. The environmental interpretations of the CRP core from other workers using sedimentological and paleontological indicators are used to infer environmental conditions that are likely to have influenced the marine palynomorph assemblages. Paleontological and sedimentological analysis suggests that both cycles were deposited in cold conditions, with sea ice and melt water influence, although the upper Oligocene assemblage is inferred to have existed in colder marine conditions, with more prolonged sea ice cover and less associated fresh water input than the assemblage of early Oligocene times. The application of modern analogues for some of the marine palynomorph taxa identified suggest the presence of sea ice, and occasionally lowered salinity in both cycles. This is broadly consistent with the findings of the other paleoenvironmental studies on the CRP cores.

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## 1. Introduction

The early history of the Antarctic ice sheet has fascinated geologists for the three decades since the Glomar Challenger drilled the first offshore cores in the Ross Sea in late 1972, and showed that Antarctic

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glaciation was not two million but at least 25 million years old (Hayes and Frakes, 1975). This led to a series of off-shore drilling projects in McMurdo Sound, the latest of which is the Cape Roberts Project (CRP), which in the austral summers of 1997–1999 cored through the margin of the Victoria Land Basin (Fig. 1). The Cape Roberts Project penetrated a 1500-m-thick stratal record of coastal glaciomarine sediments between 34 and 17 Ma old with 97% core recovery (Fig. 2) (Davey et al., 2001; Florindo et al., 2005). The strata are characterised by cyclic repetition of facies in a glaciomarine setting seaward of the rising Transantarctic Mountains. Each of the 47 cycles is bounded by an erosion surface, the result of grounding of an ice margin as it advanced over near-shore coastal sediments. The cycles are interpreted to be a record of glacial-interglacial episodes involving significant (c. 50 m) changes in eustatic sea level (Naish et al., 2001a).

A number of techniques have been applied to the CRP cores to make interpretations about changes in depositional environment and climate from early Oligocene to early Miocene times, as well as intracycle changes. These include smectite data (Ehrmann, 2000, 2001), sedimentological studies, e.g. Atkins (2001), van der Meer (2000), Fielding et al. (2001), comple-

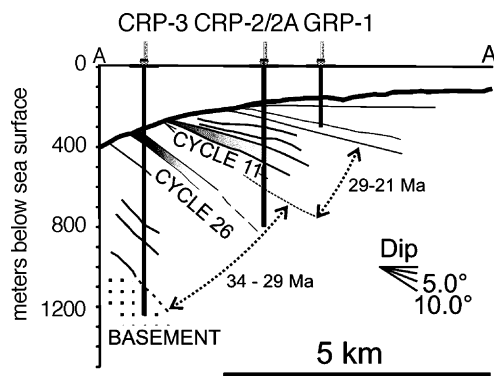


Fig. 2. An interpreted seismic section of the strata beneath the Cape Roberts Project drill sites, showing the stratigraphic relationship between the three drill holes, and the strata dipping offshore (A–A' from Fig. 1). The two intervals highlighted gray are Cycles 26 and 11, the subject of this study.

mented by paleontological investigations, e.g. Taviani and Beu (2001, 2003), Galeotti et al. (2000), Dingle and Majoran (2001), Watkins et al. (2001), Strong and Webb (2001). Many of these paleontological studies were hampered by the poor preservation of the fossil record. In contrast, marine palynomorphs (dinoflagellates, prasinophyte algae and acritarchs) are the fossils found in the relative abundance, and most continuously, throughout the CRP cores (Hannah et al., 1998, 2000, 2001a). Many of marine palynomorph forms encountered had not previously been described, or linked with modern analogues, making it difficult to infer depositional environments. However the assemblages reported here show characteristics and patterns that we believe are environmentally significant.

In this article, we present two marine palynomorph data sets from two glacio-eustatic sedimentary cycles from the CRP cores, one from the early Oligocene (Cycle 26) and the other from the late Oligocene (Cycle 11) (Fig. 3). In order to understand the changes between the two cycles, the paleoenvironmental interpretations from other investigations on the CRP cores are reviewed and environmental conditions likely to have influenced the composition of the marine palynomorph data set are suggested. Paleontological interpretations using modern analogues of the marine palynomorph dataset are then tested against the environmental interpretations derived from the paleontological and sedimentological studies.

Cycle 26 is 78.76 m thick, and occurs between 16.72 and 95.48 m below the sea floor (mbsf) in CRP-3. Chronostratigraphy of the cycle is well constrained by strontium isotope dates, magnetostratigraphic

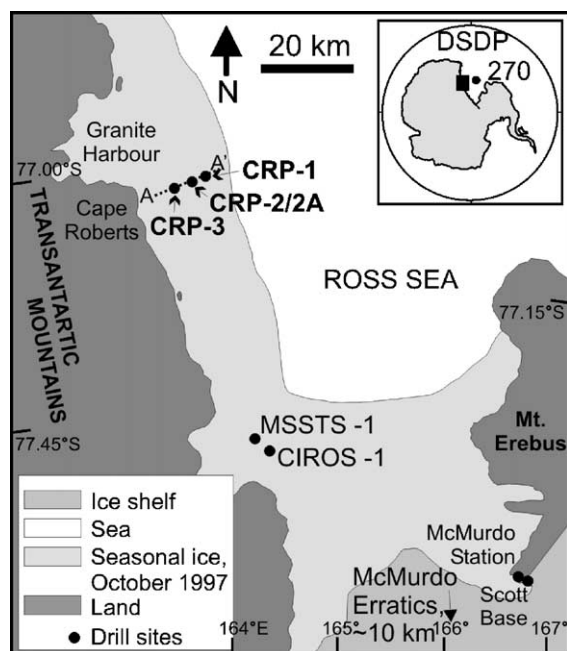


Fig. 1. Location map of the western Ross Sea region. The location of the three Cape Roberts Project drill sites is shown, along with the CIROS-1 and MSSTS-1 drill sites, and the McMurdo glacial erratics. Inset (A) shows the location of DSDP Site 270 in the Ross Sea.

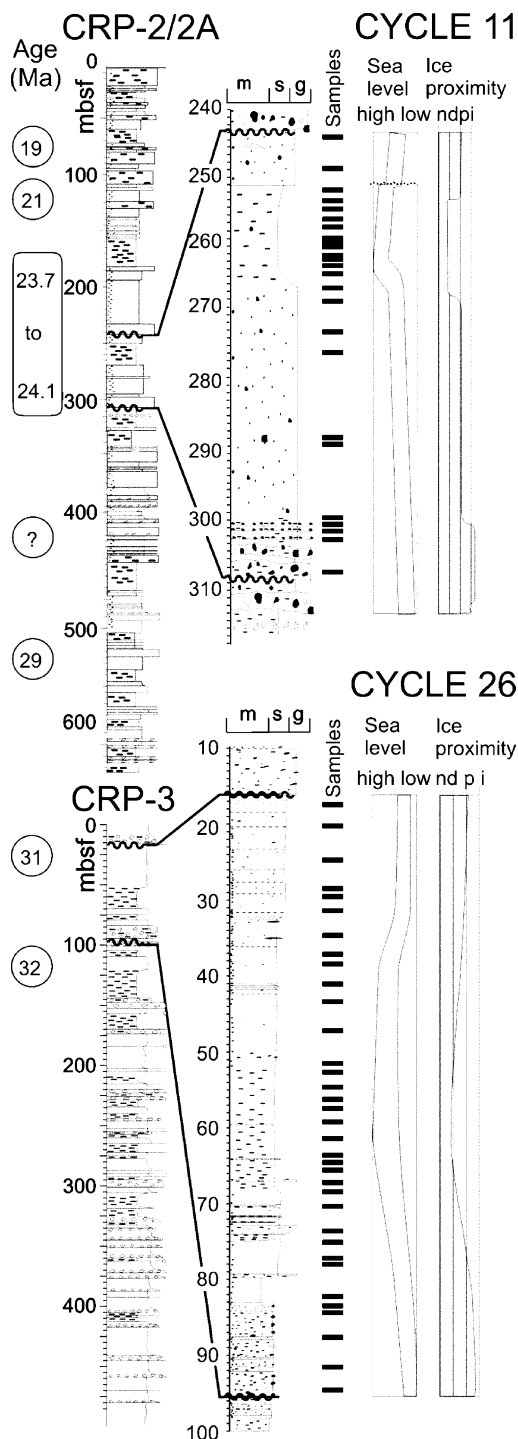


Fig. 3. Composite log of CRP-2/2A and CRP-3, showing the location of the samples used in this study. Key age constraints (from Wilson et al., 2000a,b; Hannah et al., 2001b) are included to the left of the log. Ice proximity and water depth estimations are from Naish et al. (2001b). “n”=non-glacial, “d”=ice distal, “p”=ice proximal, “i”=ice contact, “m”=mud, “s”=sand, and “g”=gravel.

phy, and two biostratigraphic first appearances (Hannah et al., 2001b). The three strontium ages, at 10.88, 29.94, and 47.55 mbsf are all 30.9, 31.0 and 30.9 Ma ( $\pm 0.8$  Ma), respectively. Given the errors on the strontium dates, the length of the cycle cannot be constrained to less than 1 Ma. However, the very small distribution of age results, the first appearance of the diatom *Cavitatus jouseanus* (30.9 Ma) at 48.44 mbsf, and the time series modelling of Naish et al. (2001a) suggests that a cycle duration of Milankovitch periodicities is likely.

Cycle 11 is 63.95 m thick, spanning 242.7 to 306.65 mbsf in CRP-2A. Its base is correlated with the beginning of the positive  $\delta^{18}\text{O}$  isotope excursion that marks the Mi-1 event. The erosional unconformity between Cycles 9 and 10 is interpreted to represent up to 250 ka of deposition lost to erosion and non-deposition as the Antarctic ice sheet advanced at the height of this event (Naish et al., 2001a). While this cycle contains abundant biostratigraphic, argon–argon, and strontium isotope dates, there are two possible age models. Wilson et al. (2000a,b) and Naish et al. (2001a), suggest that the entire cycle is within magnetozon C6Cn.3n (which has a duration of 119 ka). This interpretation allocates Cycles 10 and 11 a duration of only 40 ka each, with the remaining 39 ka lost to erosion at the top of Cycle 10. An alternative view is presented by Lavelle (2000), who suggested that the lower part of Cycle 11, below 180 mbsf, could be interpreted to have an age of between 24 and 31 Ma. The former interpretation is preferred, following Naish et al. (2001a).

## 2. Materials and methods

### 2.1. Sample selection

The samples for this study came from the Cape Roberts Project core stored at the Alfred Wegener Institute in Bremerhaven, Germany. We took more or less evenly spaced samples, though with a bias towards finer-grained sediments which were expected to be more productive, through the two glacioeustatic sedimentary cycles. This equates to an average sample spacing of 2.1 m in Cycle 26, and 2.4 m in Cycle 11.

### 2.2. Palynological processing methods

The sample processing procedure followed that described by the Cape Roberts Science Team (1998), and Simes and Wrenn (1998), although differs in two respects: microwave digestion was not used in the

present study, nor was a *Lycopodium* spike added. A description of the methods used is included in Prebble et al. (this issue).

The dry weight of sediment was recorded before processing, and a known amount of the remaining residue was mounted onto each slide, so that the palynomorph count may be expressed in terms of grains per gram of sediment. Every part of a slide was examined for palynomorphs. This technique assumes that a negligible amount of material is lost during processing, and that every slide is representative of its sample (Truswell, 1983; McMinn and Wells, 1997). Care was taken to ensure that no material was lost accidentally.

### 2.3. Microscope technique

The slides were studied using a Leitz Diaplan microscope, under both normal light and differential interference contrast. Photographs were taken of well-preserved representative grains using a Leica DFC 280 digital camera. The photographs were not retouched in any way. 300 specimens per sample were counted where possible.

### 3. Marine palynomorph assemblage

The samples contain a sparse palynoflora of moderate diversity. Absolute abundance between samples is variable, even between samples of similar grain size

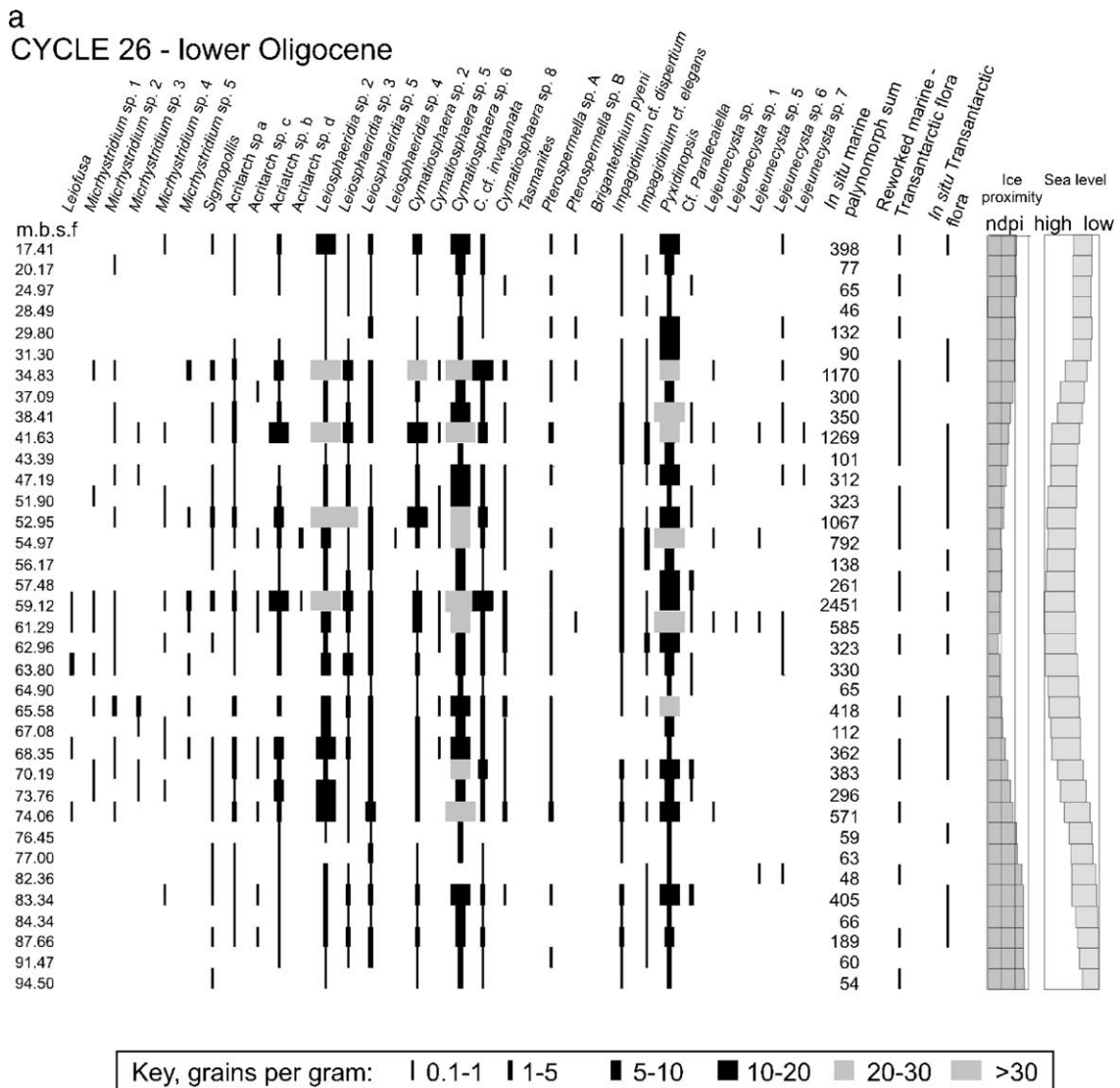


Fig. 4. Range charts of marine palynomorphs found in Cycle 26 (lower Oligocene), and Cycle 11 (upper Oligocene). Ice proximity and sea level estimates from Naish et al., 2001b.



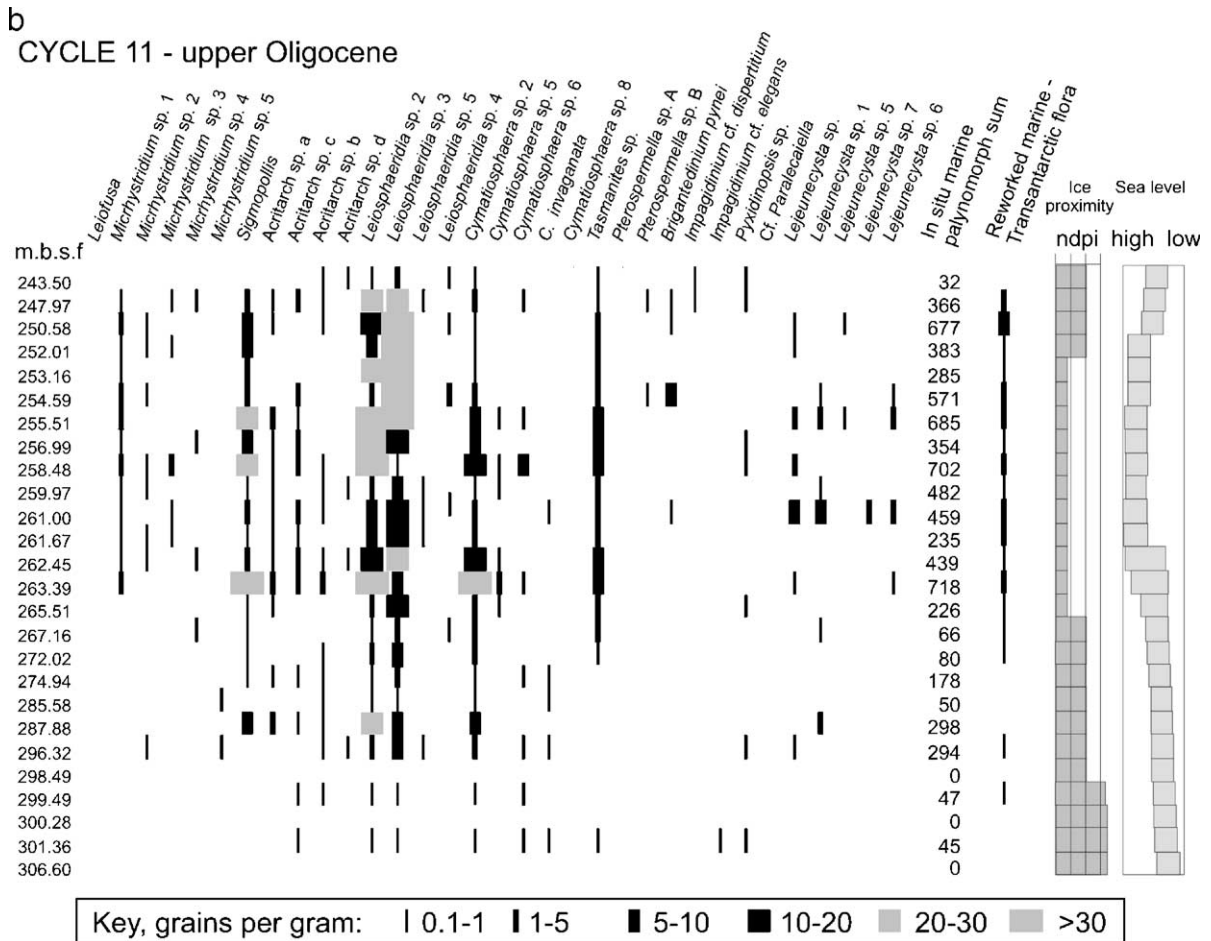


Fig. 4 (continued).

and lithofacies. Marine palynomorphs average around 56 specimens per gram across all the samples, with dinoflagellate cysts averaging nine per gram. Marine palynomorphs were sufficiently abundant that a count of at least 300 was obtained in 30% of the samples, and a count of more than 50 in 72% of the samples.

The abundances of each of the 48 taxa recognised are shown for each sample in Fig. 4, and the most abundant taxa are illustrated in Fig. 5. Many have not been described formally before, and for these informal, open nomenclature has been adopted, pending formal description elsewhere. All palynomorphs presented here are described as 'marine' palynomorphs—a separate paper (Prebble et al., this issue) describes those palynomorphs known to be terrestrial. Given the difficulties applying modern analogues to taxa of this age, the possibility that some are fresh water aquatic forms cannot be discounted. Most taxa are found throughout both cycles, but some are restricted to one cycle. The

names assigned to taxa are those proposed by Hannah et al. (1998, 2000, 2001a,b).

Both cycles are dominated by the acritarchs, *Leiosphaeridia* sp. 2, *Leiosphaeridia* sp. 3, and the prasinophyte alga, *Cymatiosphaera* sp. 2. Less dominant, but persistent taxa in both cycles include *Michrystidium* spp. 1–4, *Acritarch* sp. a, and *Lejeunecysta* sp. 6.

The lower Oligocene Cycle 26 contains no *Tasmanites* sp. or *Brigantedinium pynei*, rare cf. *Paralecaniella* sp., and lower abundances of *Acritarch* sp. c than the upper cycle. The cycle contains *Leiofusa*, cf. *Paralecaniella* sp., and *Pterospermella* sp. A, *Impagidinium* cf. *disperitium* and *I. cf. elegans*. *Cymatiosphaera* sp. 6 and *Pyxidinospis* sp. are both abundant.

The upper Oligocene Cycle 11 is characterized by an absence of *Leiofusa* sp., *C. invaganata*, *Cymatiosphaera* sp. 8, and *Pterospermella* sp. A. It has very low numbers of *Acritarch* sp. b, *Impagidinium* and *Pyxidinospis*. It contains *Tasmanites* sp. and *B. pynei*,

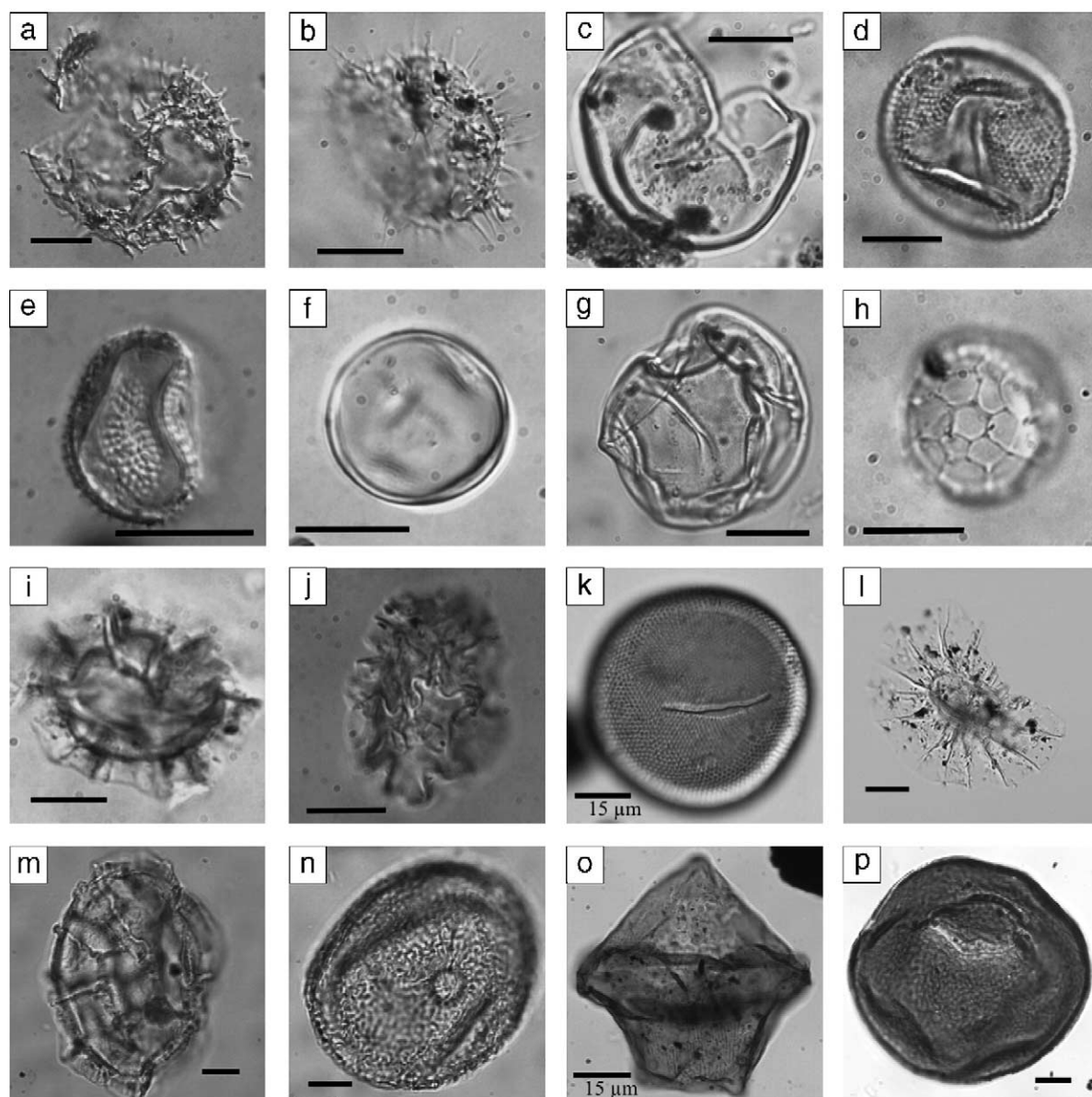


Fig. 5. Illustrations of the most common marine palynomorphs found in this study: (a)–(g) are acritarchs, (h)–(l) are the phycoma of prasinophyte algae, while (m)–(p) are dinoflagellate cysts. All scale bars 10  $\mu\text{m}$  unless stated. (a) *Micrhystridium* sp. 2. 40  $\mu\text{m}$ . (CRP-3, 51.9 mbsf)(Core and sample depth)[O52/4][England finder location]. (b) *Micrhystridium* sp. 3. 18  $\mu\text{m}$ . (CRP-3, 65.58 mbsf)[O31/2]. (c) *Sigmopollis*. 32  $\mu\text{m}$ . (CRP-2A, 255.51 mbsf)[P33/1]. (d) *Acritarch* sp. a. 29  $\mu\text{m}$ . (CRP-3, 41.63 mbsf)[T54/2]. (e) *Acritarch* sp. b. 22  $\mu\text{m}$ . (CRP-3, 41.63 mbsf)[U39]. (f) *Leiosphaeridia* sp. 2. 20  $\mu\text{m}$ . (CRP-2A, 263.39 mbsf)[V22/1]. (g) *Leiosphaeridia* sp. 3. 30  $\mu\text{m}$ . (CRP-2A, 247.97 mbsf)[V48/2]. (h) *Cymatiosphaera* sp. 2. 18  $\mu\text{m}$ . (CRP-3, 41.63 mbsf)[V51]. (i) *Cymatiosphaera* sp. 6. 30  $\mu\text{m}$ . (CRP-3, 34.83 mbsf)[R43]. (j) *C. ? invaginata*. 30  $\mu\text{m}$ . (CRP-3, 37.09 mbsf)[K43/2]. (k) *Tasmanites* sp. 72  $\mu\text{m}$ . (CRP-2A, 250.58 mbsf)[U42]. (l) *Pterospermella* sp. a. 48  $\mu\text{m}$ . (CRP-3, 68.35 mbsf)[C44/3]. (m) *Impagidinium cf. elegans*. 64  $\mu\text{m}$ . (CRP-3, 56.17 mbsf)[F15]. (n) *Pyxidinospis* sp. 56  $\mu\text{m}$ . (CRP-3, 17.41 mbsf)[K14/1]. (o) *Lejeunecysta* sp. 6. 70  $\mu\text{m}$ . (CRP-2A, 261.67 mbsf)[F35/1]. (p) *B. pynei*. 80  $\mu\text{m}$ . (CRP-2A, 255.51 mbsf)[W37/3].

and it has higher abundances of *Lejeunecysta* sp. 1 and *Sigmopollis* than the lower Oligocene cycle.

These broad changes in palynomorph composition have been documented previously by Hannah et al. (2000, 2001a,b). In particular, those authors note that

the last regular appearances of *Pyxidinospis* sp., *Leiofusa*, and *I. cf. elegans* occur in the lower part of CRP-2A (316.50, 307.12 and 444.76 mbsf, respectively). The present dataset demonstrates that previous results are repeatable, and presents results at greater resolution.

#### 4. Reworking, taphonomy and environmental controls on marine palynomorph distribution

##### 4.1. Marine palynomorph compositions environmentally controlled

An assumption central to our interpretation of the changes in marine palynomorph composition documented between the two cycles is that composition is controlled principally by local environmental conditions. We base this on the observation that the distribution of modern marine palynomorphs has been shown to be controlled by various environmental parameters (e.g. Mudie, 1992; Rochon et al., 1999), including temperature, salinity, nutrient availability and ice cover.

Taphonomic factors may also have influenced the composition of the assemblage. We first consider three of these:

- 1) regional reworking (from much older strata e.g. from Eocene into Oligocene sediments),
- 2) local reworking (locally between and within cycles), and
- 3) differential preservation.

Most elements of the dinoflagellate assemblage now termed the Transantarctic Flora are not found above the Eocene–Oligocene boundary in the Victoria Land Basin, but others persist until around the early–late Oligocene boundary (c. 28.5 Ma) (Hannah, 1997; Raine et al., 1997; Levy and Harwood, 2000). Following these authors, three taxa, *Spinidinium macmurdoense*, *Vozzhennikovia apertura*, and *Deflandrea antarctica*, have been counted as in situ specimens in the early Oligocene Cycle 26 and as reworked specimens in the upper Oligocene Cycle 11. All other taxa of the Transantarctic Flora have been treated as reworked in this study.

The numbers of prasinophyte algae and acritarchs reworked from Eocene strata are difficult to quantify. This is because the stratigraphic range of these palynomorphs is poorly known. However, in a study of marine palynomorphs from the CIROS-1 core Hannah (1997) reported that in the Eocene section acritarchs and prasinophyte algae do not reach over 5% of the total palynomorph count, whereas the post Eocene section contains abundant acritarchs (over 70%). We conclude that while there is likely to be some undetected reworking of prasinophyte algae and acritarchs from older sediments into Oligocene strata, reworking of these groups is not likely to have significantly affected the counts presented here.

The extent of reworking of marine palynomorphs within the Oligocene is also difficult to quantify. However, given the low abundance of some taxa (e.g. *Pyxidopsis* sp. and *Impagidinium* sp.) in the upper Oligocene cycle compared to the lower Oligocene cycle, and the very rapid changes of relative abundance even within each cycle, reworking between, and within the cycles is not likely to have significantly affected the final assemblage in most samples. In summary, we conclude that the counts obtained for each cycle overwhelmingly represent the biota present at the time of deposition.

Recent laboratory studies have shown that some types of dinoflagellates are more susceptible to post-depositional degradation by oxidation than others (Zonneveld et al., 1997; Hopkins and McCarthy, 2002; McCarthy et al., 2003). They have shown that Proto-peridinioid dinocysts (*Brigantedinium* and *Lejeune-cysta* in the present study) are more susceptible to oxidation than other dinoflagellates. This suggests that taxa such as *Brigantedinium* were a greater part of the life assemblage than the relatively low numbers found in the fossil assemblage suggest.

#### 5. Environmental conditions of the Ross Sea and Victoria Land Coast during the Oligocene from the CRP cores

The environmental interpretations derived from the Cape Roberts Project are summarized in Fig. 6.

##### 5.1. Paleontology

Most Oligocene fossil assemblages from the Victoria Land Basin are less abundant and diverse than those recovered from sediments of Eocene age that are found within the McMurdo Glacial Erratics, interpreted to have been deposited in a temperate, largely ice free, climate (e.g. Wilson et al., 1998; Stilwell and Zinsmeister, 2000). Marine microfossil workers have suggested that cool, or cold, conditions prevailed in the Ross Sea during the early Oligocene (Dingle and Majoran, 2001, ostracods; Watkins et al., 2001, calcareous nannofossils), and conditions were possibly similar to modern-day Patagonia or Alaska (Taviani and Beu, 2001, 2003, marine macrofossils). Others have suggested that glacial or sea ice was present, and contributing a significant fresh water influx (Strong and Webb, 2001, foraminifera), while Watkins et al. (2001, calcareous nannofossils) also suggest that an ‘abnormal surface water chemistry’ prevailed.



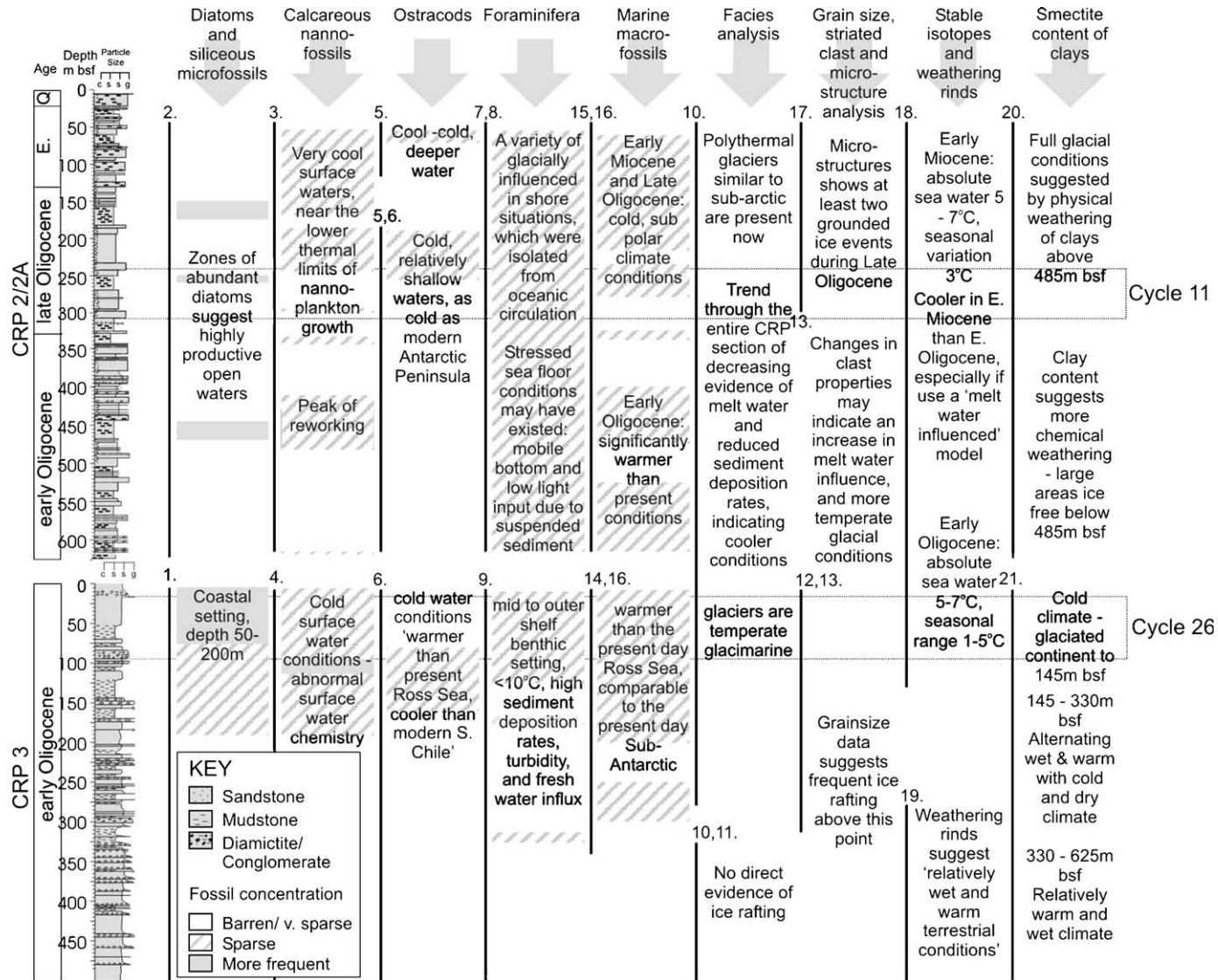


Fig. 6. Depositional environmental conditions of CRP32/2A and the upper part of CRP-3. The numbers on the figure refer to the following references: 1: Scherer et al. (2000), 2: Harwood and Boharty (2001), 3: Watkins and Villa (2000), 4: Watkins et al. (2001), 5: Dingle (2000), 6: Dingle and Majoran (2001), 7: Strong and Webb (2000), 8: Galeotti et al. (2000), 9: Strong and Webb (2001), 10: Powell et al. (2001), 11: Fielding et al. (2001), 12: Barrett (2001), 13: Atkins (2001), 14: Taviani and Beu (2001), 15: Taviani et al. (2000), 16: Taviani and Beu (2003), 17: van der Meer (2000), 18: Lavelle et al. (2001), 19: Hall et al. (2001), 20: Ehrmann (2000).



Macrofossil assemblages recovered from upper Oligocene strata in CRP-2/2A suggest that the region was then subjected to cold, subpolar conditions (Taviani et al., 2000; Taviani and Beu, 2003). Foraminifera from the same core suggested a glacially influenced environment (Galeotti et al., 2000). Scherer et al. (2000) reported some diatoms from CRP-2A with possible sea ice affinity. The lack of change in ostracod assemblages suggests that sea conditions changed little over the Oligocene–Miocene boundary, but suggest waters as cold as is found at the modern Antarctic Peninsular (Dingle, 2000).

The most complete record of Oligocene terrestrial vegetation from the Ross Sea Region to date is the miospore (pollen and spore) assemblage extracted from the CRP cores (Askin and Raine, 2000; Raine and Askin, 2001; Prebble et al., *this issue*; Raine and Prebble, in preparation). The assemblage is dominated by *Nothofagidites* pollen. Two different assemblages were recognised by Askin and Raine (2000): a lower Oligocene vegetation was inferred to be low shrub or closed forest of smaller stature and floristic richness than the Eocene, with the vegetation and climate of the present day Magellanic region suggested as a modern analogue, and an upper Oligocene lower diversity assemblage, containing all of the elements of the assemblage found in the Meyer Desert Formation, suggesting a parent vegetation that had become restricted to a sparse tundra vegetation, growing in a periglacial climate. A subsequent study on additional material by Prebble et al. (*this issue*) yielded a more varied upper Oligocene assemblage indicating only a slight decrease in diversity and reduced temperature.

A study of phytoliths (siliceous plant microfossils) from the CRP core was hampered by sparse assemblages, and a lack of suitable modern analogues (Thorn, 2001). Despite this, a cool climate was inferred to occur throughout both cores, but with a few forms possibly indicative of warmer climates in the early Oligocene assemblage.

### 5.2. Sedimentology and petrology

Sedimentological studies of the Cape Roberts core recognised an increase of glacial influence during the early Oligocene using facies analysis (Powell et al., 2001; Fielding et al., 2001), while grain size data and analysis of striated clasts suggests an increase in the incidence of ice rafting at c. 250 mbsf in CRP-3, in early Oligocene times (Barrett, 2001; Atkins, 2001). In contrast, below this point in CRP-3, facies analysis shows no direct evidence of ice-rafting (Powell et al.,

2001; Fielding et al., 2001), and analysis of weathering rinds and smectite content suggests relatively wet and warm terrestrial conditions (Hall et al., 2001; Ehrmann, 2001). The smectite content studies recognise a period of alternating ‘warm and wet’ and ‘cold and dry’ climate between 145 and 330 mbsf in CRP-3, before cold climate glacial conditions prevail in the top 145 m of the core. The analysis of striated clasts, micromorphology, and facies analysis suggest that the style of glaciation changed during the Oligocene, with less melt water present, and grounded ice events at the drill site, by the late Oligocene suggesting colder conditions (Atkins, 2001; van der Meer, 2000; Fielding et al., 2001; Powell et al., 2000, 2001). The smectite content of strata from the CRP-2A core suggests more physical weathering, inferred to represent full glacial conditions, above 485 mbsf (late Oligocene and some early Oligocene time), and suggests more extensive ice free areas below 485 mbsf, during the early Oligocene (Ehrmann, 2000). Water temperature estimates derived from stable isotopes from macrofossils suggest an absolute sea water temperature of 5–7 °C, with a seasonal range of 1–5 °C during the lower Oligocene, and 3 °C during the upper Oligocene (Lavelle et al., 2001).

### 5.3. Marine palynomorphs and environment

From the environmental interpretations presented to date on the CRP core, it is clear the marine palynomorph assemblage in both Cycle 11 and Cycle 26 existed in a cold environment, with a sea ice influence. Some fresh water influence has been detected in the lower Oligocene cycle, while colder conditions, possibly with less fresh water influence are likely to have prevailed in the upper Oligocene cycle.

## 6. Modern analogues and environmental interpretation

Modern analogues of marine palynomorphs are commonly used to infer Quaternary paleoenvironments (e.g. Mudie, 1992; McMinn and Wells, 1997; Rochon et al., 1999). The potential for modern analogues of marine palynomorphs for reconstruction of Ross Sea depositional environments has been recognised, and some first steps taken, by Wrenn et al. (1998) for strata of Miocene age, and Hannah (1994, 1997) for changes across the Eocene–Oligocene boundary. Modern environmental analogues for some of the marine palynomorphs recorded in this study are presented in Table 1. The modern analogues assembled for the taxa identified in the CRP cores, espe-

Table 1

Modern environmental analogues of the marine palynomorph taxa identified in this study

Genera	Reference	Modern environmental analogue
<i>Leiosphaeridia</i>	Mudie, 1992	Found most commonly under seasonal pack in the arctic. An 'ice margin indicator'. Has a $-2$ to $+4$ °C Arctic Summer SST range.
<i>Sigmopollis</i>	Mudie, 1992	Low salinity and ice marginal taxon.
<i>Cymatiosphaera</i>	Mudie, 1992	Most common is normal to low salinity nutrient-rich waters.
<i>Pterospermella</i>	Mudie, 1992	Increases towards glacier and melt water plumes. Low salinity taxa from stratified water masses.
<i>Tasmanites</i>	Tappan, 1980	Autotrophic.
	Guy-Ohlson, 1996	Possibly low temperature, and reduced salinity water.
<i>Impagidinium</i>	Harland et al., 1998	Only present of north of 60° S in a north–south transect of surface sediments in the Southern Ocean.
	Zippi, 1992	Occurs in maximum frequencies in temperate to tropical water masses.
	Rochon et al., 1999	A preference for warmer sea surface temperature, normal salinity and low ice cover. The main exception is <i>I. pallidum</i> , which tolerates cold temperatures and prolonged ice cover.
	Edwards and Ardlle, 1992	General trend towards increasing relative abundance with increasing sea surface temperatures and water depth.
<i>Pyxidinopsis</i>	Rochon et al., 1999	<i>P. reticulata</i> has scattered occurrences of mid latitudes of North Atlantic, but is not found polewards of 60° N. Preference for high year-round temperatures and no ice cover.
<i>Brigantidinium</i>	Rochon et al., 1999	Wide range, but is slightly more abundant in low salinity or when SST < 10 °C, or low nutrient availability. Heterotrophic.
	Matsuoka, 1992	Around seas of Japan, is more common in northern waters, which are influenced by a relatively cold current.
Prasinophyte algae	Wrenn et al., 1998	Commonly associated with low temperature, enhanced productivity and a stratified water column, with low salinity waters overlying low oxygen to anoxic bottom waters.
	Guy-Ohlson, 1996	Linked to marginal marine freshwater depository settings, or their influence.

cially the acritarchs and prasinophyte algae, suggest that the marine conditions were cold, with persistent ice cover, and lowered salinity. As seen in Fig. 6, this is consistent with the findings of other CRP workers, lending weight to the validity of the use of modern analogues to understand this data set.

Acritarchs and prasinophyte algae are found associated with low diversity dinoflagellate assemblages (similar to those found in the present study) in the high latitudes of the Northern Hemisphere (e.g. Mudie, 1992; Zippi, 1992; Mudie and Harland, 1996; Rochon et al., 1999). In contrast, studies of modern high latitude sediments from the Southern Hemisphere have found very low diversity palynomorph assemblages (Harland et al., 1998), with no taxa similar to those found in the Oligocene sediments of this study. In recent sediments, *Leiosphaeridia* sp. and *Sigmopollis* sp. are both found in high numbers in ice marginal environments, under seasonal ice, and in low salinity and temperature environments (Mudie, 1992). *Cymatiosphaeridia* sp., (and other prasinophyte algae) are also found in large numbers in low salinity water masses (Mudie, 1992; Wrenn et al., 1998). The dominance of these forms in both of the Oligocene cycles investigated here is a strong indication that the sea ice was present,

as was regular fresh (melt) water input, creating stratified water masses, possibly also with high nutrient input.

Environmental interpretations using modern analogues of the dinoflagellate taxa are less certain, principally because many modern dinoflagellate genera contain species that inhabit a diverse range of environments. Members of the genus *Impagidinium*, for example, are found in maximum frequencies in temperate and tropical water masses (Zippi, 1992; Edwards and Ardlle, 1992), but one genus, *I. pallidum*, tolerates cold temperatures and prolonged ice cover (Rochon et al., 1999). Given that many other indicators point to the presence of sea ice during the deposition of both Cycle 11 and Cycle 26, and the observation that the two taxa attributed to *Impagidinium* in the present study have little resemblance to *I. pallidum*, modern analogues of this group at a generic level cannot be reliably used for environmental interpretation in this context. The only representative of the genus *Pyxidinopsis* for which the modern distribution has been documented suggests that this genus may have a preference for warmer temperatures and ice free conditions (Rochon et al., 1999). Again, given the likely presence of sea ice, applying this modern

analogue directly to the Cape Roberts assemblages is not robust. Another dinoflagellate genus for which a modern analogue is available is *Brigantedinium*. This genus also has a wide climatic range in recent times, but is slightly more abundant in low salinity environments or where the sea surface temperature is less than 10 °C (Rochon et al., 1999; Matsuoka, 1992). This genus is present in Cycle 11, but not in Cycle 26, so could be an indication of colder conditions in this part of the Upper Oligocene strata.

## 7. Conclusions—marine palynomorphs and environment

Palynomorph assemblages through two glacioeustatic cycles have been documented. The lower Oligocene assemblage differs from the upper Oligocene assemblage by the presence of *Pyxidinospis* sp. cf. *Impagidinium* sp., different types of *Cymatiosphaera*, and a lack of *Tasmanites* sp and *Brigantedinium* sp. The upper Oligocene Cycle 11 assemblage does not contain *Leiofusa* sp., *C. invaginata*, *Cymatiosphaera* sp. 8, and *Pterospermella* sp. A. It has very low numbers of *Acritarch* sp. b, *Impagidinium* and *Pyxidinospis*. It contains *Tasmanites* sp. and *B. pynei*, and it has higher abundances of *Lejeunecysta* sp. 1 and *Sigmo-pollis* than the lower Oligocene cycle.

The differences between the two assemblages are considered to reflect environmental changes between the two cycles. The compilation of other worker's research suggests that both of these assemblages existed in cold water conditions, associated with sea ice. It is considered likely that the colder marine conditions identified in Cycle 11 is reflected in the different composition of the marine palynomorph assemblage.

Modern analogues of the marine palynomorphs broadly confirm these conclusions. They suggest that sea ice was present during the deposition of both cycles. The modern analogues also suggest that both cycles are likely to have had significant fresh water input and water stratification. Although the assemblage clearly change between Cycle 26 and Cycle 11, the application of the modern analogues identified to date are not sufficient to be specific about any change in environmental conditions.

Marine palynomorphs were recovered from the majority of lithologies of the Cape Roberts Core, with more extensive distribution than any other fossil group. The results presented here suggest that they have the potential to be a powerful paleoenvironmental tool in southern high-latitude localities, where other fossil groups are sparse.

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