

Diversity and Palaeoenvironmental Significance of Late Cainozoic Marine Palynomorphs from the CRP-1 Core, Ross Sea, Antarctica

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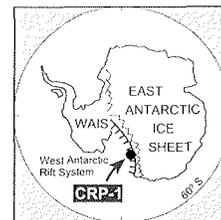
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Abstract - The first core of the Cape Roberts Project, CRP-1, penetrated a Quaternary and lower Miocene section rather than the anticipated Palaeogene sediments. Initial palynologic study was conducted at the Crary Science and Engineering Laboratory, McMurdo Station, concurrent with drilling. Rapid and environmentally safe sample processing was made possible by the use of a focused microwave digestion unit that scrubbed acid fumes. *In situ* and/or reworked dinocysts (dinoflagellate cysts), acritarchs (leiospheres and acanthomorphs), and prasinophyte phycomata are present in the 35 samples studied. Overall, the CRP-1 assemblages are similar to Arctic marine palynomorph assemblages that are used there as ice margin indicators. Some of the acanthomorph acritarchs recovered from the CRP-1 core closely resemble cysts of extant Antarctic autotrophic sea-ice dinoflagellates. It is possible that some of these acanthomorphs are actually dinocysts, and could be used as indicators of sea-ice conditions similar to today.

Most of the *in situ* marine palynomorphs are undescribed taxa and thus are presently of little biostratigraphic value. Dating of the core was based on diatom, palaeomagnetic and strontium isotope studies. The upper 43.55 mbsf of the core are Quaternary in age and the rest of the core, down to the bottom at 147.69 mbsf, is of early Miocene age.

Although not biostratigraphically significant, the dinocysts are the first *in situ* Quaternary and Miocene dinocysts reported from East Antarctica, and constitute the most diverse assemblage recovered from any firmly dated Neogene section from Antarctica. In addition, they confirm that cyst-producing dinoflagellates were present in Antarctic waters during the Neogene and Quaternary.

The core can be divided into three intervals based on their palynomorph assemblages (Quaternary, 0-43.55 mbsf; lower Miocene, 43.55-99.10 mbsf; and lower Miocene, 99.10-147.69 mbsf). The distinctive palynomorph assemblages are interpreted to reflect changing climatic conditions that prevailed at the time of deposition. Overall, conditions appear to have deteriorated up-section.



INTRODUCTION

The Cape Roberts Project is an international drilling programme supported by Australia, Germany, Italy, New Zealand, the United Kingdom and the United States of America. Its goal is to continuously core 1 200 m of east dipping strata shown by seismic surveys to underlie the Ross Sea offshore from Cape Roberts, East Antarctica. These units were thought to range in age from Oligocene to middle Cretaceous. Comparable units do not crop out in East Antarctica; thus the submarine units are unique and of significant scientific value. Studies of these deposits will shed considerable light on the evolution of the Ross Sea Basin, the Transantarctic Mountains, the East Antarctic Ice Sheet, and the changing Antarctic climate during this time interval (Barrett, 1997).

The goal of the first core was to recover upper Palaeogene sediments. However, CRP-1 cored early Miocene strata (Fig. 1). Subsequent cores to be drilled west of the CRP-1 site are intended to penetrate older Cainozoic and Cretaceous deposits (Barrett, 1997). Details of the first drilling season and the preliminary scientific studies conducted in the U. S.

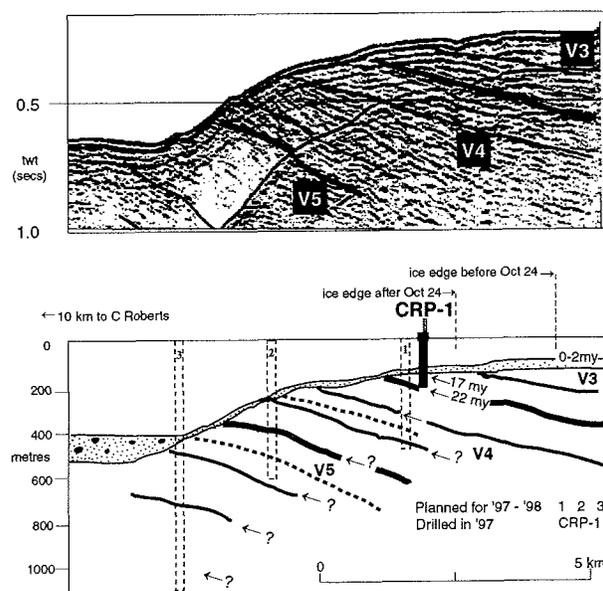


Fig. 1 - Interpreted seismic section showing part of the dipping submarine sedimentary section and subsurface seismic Units V3, V4 and V5 off Cape Roberts (Cape Roberts Science Team, 1998; adapted from Barrett, 1997).

National Science Foundation's (NSF) Crary Science and Engineering Center (CSEC), at McMurdo Station, are reported in the Initial Report on CRP-1 (Cape Roberts Science Team, 1998).

Palynology is one of the subdisciplines of micro-palaeontology intended to provide biostratigraphic support for the drilling programme in the Palaeogene-Cretaceous target section. A palynologic processing facility was set up in CSEC so that sample processing and analysis could be conducted concurrent with drilling. Coring recovered an unexpectedly young post-Oligocene section containing rare to moderately common palynomorphs, including spores, pollen, prasinophyte phycocysts, acritarchs, and dinocysts. Diverse terrestrial palynomorphs also were recovered from the core and are treated in Raine (this volume).

Most of the marine palynomorphs were either new, undescribed species or reworked taxa (Cape Roberts Science Team, 1998; Hannah et al., this volume). Consequently, none were age diagnostic for the units cored. Fortunately, diatoms were abundant and, in concert with palaeomagnetic and strontium isotope analyses provided ages for the core. They indicate that the uppermost 43.55 mbsf of CRP-1 are Quaternary in age, and the lower 104.45 mbsf are of early Miocene age (Fig. 2; Cape Roberts Science Team, 1998; Bohaty et al., this volume; Harwood et al., this volume; Lavelle, this volume; Roberts et al., this volume).

Although the marine palynomorphs were of no biostratigraphic utility, they are of palaeoenvironmental significance. This paper deals with that aspect of the assemblages. In this paper we use the term "dinoflagellate" to refer to the motile stage and "dinocyst" to refer to the resting, or inactive, stage of the organism's life cycle. Complete scientific names of all dinoflagellate and dinocyst species mentioned in this paper are given in appendix 1.

METHODS AND MATERIALS

The most southerly palynologic processing laboratory in the world was established to support drilling operations. This was the first time that palynologic samples had been processed and analyzed in Antarctica. Sample processing is a critical step in any palynologic study (Wrenn, 1998). The procedures used in this study were based on those of Gray (1965) and Barss & Williams (1973). Simes & Wrenn (this volume) provide a detailed discussion of palynologic sample processing used on the Cape Roberts Project. In general, the procedure used included:

- 1) acid digestion of mineral clasts and cements in hydrochloric acid (to remove carbonates) and hydrofluoric acid (to remove silicates);
- 2) controlled oxidation (to remove unwanted organic debris);
- 3) the concentration of palynomorphs by heavy liquid separation and/or filtration on a six micron mesh filtering unit (Raine & Tremain, 1992).

Palynological sample digestion is typically conducted with cold acids in open beakers. Acidic fumes generated during mineral dissolution are vented from the fume hood

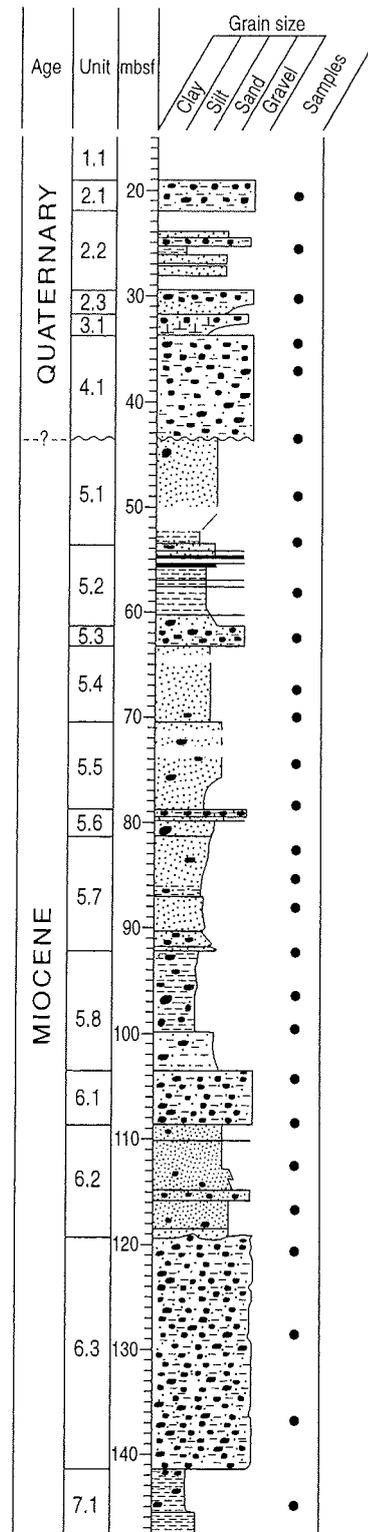


Fig. 2 - Stratigraphic column of the CRP-1 core showing the age, units, depth in meters, sedimentary grain size, lithology, and location of samples examined for palynomorphs (adapted from Cape Roberts Science Team, 1998). Some dots represent more than one sample because samples are too close together to differentiate on this diagram (Tab. 1 lists the depth of all samples studied in CRP-1).

to the atmosphere. Special consideration was required for handling harmful fumes because of the sensitive Antarctic environment. A ProLabo M401 focused microwave digestion system was used for acid digestion of the minerals because it captures and scrubs acid fumes. The digester

also accelerated processing by safely heating each sample during acid digestion.

The use of microwave digestion for palynological sample preparation was developed at the University of Sheffield, Sheffield, England. (See Ellin & McLean, 1994; Jones, 1994; Jones et al., 1995; Jones & Ellin, 1998, for discussions of the application of microwave digestion to palynologic sample processing). Our use of focused microwave technology in Antarctica demonstrated its applicability in remote areas and in situations where environmental integrity is a major concern. The speed, economy and inherent safety qualities of focused microwave digestion technology recommend it for use on offshore drilling platforms as well as on ships.

Thirty-four samples were studied during core drilling, and general results were presented in the Initial Report on the CRP-1 core (Cape Roberts Science Team, 1998). Time did not permit a detailed analysis to be conducted in Antarctica on all samples. Subsequently, detailed counts were made on 35 samples (Fig. 2), including many but not all of the samples initially examined in Antarctica. The results are presented here (Tab. 1) and in Hannah et al. (this volume). Samples were selected, where possible, from fine sand and silt units at roughly 4 m intervals. Approximately 5-6 grams of each sample were processed, except for the sample at 45.04 mbsf (this sample was initially examined in Antarctica, but no detailed count has been made since then; thus it does not appear in Tab. 1 of this paper). The lithology of that sample is fine sandstone and 10 gm were digested in the hope of increasing recovery (Simes & Wrenn, this volume). One *Lycopodium* tablet was added to each sample as a concentration spike at the beginning of processing.

RESULTS

The CRP-1 core samples studied yielded 36 species of *in situ* dinoflagellate cysts, acritarchs, and prasinophycean phycoma (Tab. 1). Most of these are new species and were assigned informal names in the Initial Report on CRP-1 core (Cape Roberts Science Team, 1998). Some of these new taxa are formally described in Hannah et al. (this volume). Selected taxa are shown on figures 3 to 5; others are illustrated in the Initial Report on CRP-1 (Cape Roberts Science Team, 1998) and Hannah et al. (this volume).

Six species of *in situ* dinoflagellate cysts were recognized in the core. Until recently, *in situ* post-Oligocene dinocysts were thought not to exist in Antarctica (McMinn, 1995). The continent's very deep (500 m) continental shelf was considered to be too unfavorable an environment in which shelf-loving dinoflagellates could flourish.

These six new CRP-1 dinocyst species described by Hannah et al. (this volume) are the first *in situ*, post-Oligocene fossil dinocysts to be reported from East Antarctica. They are also the first Neogene and Quaternary *in situ* dinocysts from any Antarctic section whose age is well constrained. Compared to dinocyst assemblages in pre-Miocene Antarctic sediments (*e.g.*, Wrenn & Hart 1988; Askin 1988; Smith 1992; Dolding, 1992; Keating 1992), this is a very sparse assemblage.

Most marine dinoflagellates occur in shelf environments, though there are species found in the oceanic realm. McMinn's (1995) explanation of the dearth of post-Oligocene Antarctic dinocysts was reasonable based on the fossil record at that time. However, biologic studies of modern sea-ice alga communities (Buck & Garrison, 1983; Garrison et al., 1987; Garrison, 1991; Stoecker et al., 1991, 1993; and others) indicate that the floating annual sea-ice and fast ice is a significant habitat for a wide variety of microbes, including dinoflagellates. Dinoflagellates are the dominant components of some of these ice-alga communities, and some of these dinoflagellates are known to produce dinocysts (Stoecker et al., 1991, 1993).

The vast expanse of annual sea-ice around Antarctica waxes and wanes with the seasons. During winter it grows outward from the continent to such an extent that it doubles the area of the continent (El-Sayed, 1985). This sea-ice can be thought of as a "floating continental shelf," at least with regard to dinoflagellate habitats, and the lack of a shallow continental shelf has been offset by its unique habitats. It may be that future research will show that the sea-ice and the adjacent water column are the main habitats of Antarctic dinoflagellates.

QUATERNARY MARINE PALYNOMORPHS OF THE CRP-1 CORE

Eight samples from the Quaternary section (0-43.55 mbsf) of the CRP-1 core yielded a low diversity, *in situ* palynomorph assemblage of rare acritarchs (9 species), very rare dinocysts (at least 3 species), and prasinophycean green algae (3 species; Fig. 3, Tab. 1). The acritarchs most probably have a marine algal affinity, and some may well be dinocysts (see below).

Rare, well-preserved prasinophyte phycoma of *Cymatiosphaera* spp. occur in the Quaternary samples. The most commonly encountered form in the Quaternary samples was *Cymatiosphaera* sp. 1, a small hyaline form bearing minute membranes that delimit lacuna on the surface of the phycoma (see Hannah et al., this volume, for a more detailed description of these and other taxa observed in the CRP-1 core).

Acritarchs are less abundant in the Quaternary section than prasinophyte phycoma and include *Sigmopollis* sp., *Leiosphaeridia* sp. 1, *Leiosphaeridia* sp. 2, *Leiosphaeridia* sp. 3, *Micrhystridium* sp. 1, *Micrhystridium* sp. 2, *Micrhystridium* sp. 5, *Micrhystridium* sp. 6, and Acritarch sp. 1; all are previously undescribed forms. *Leiosphaeridia* sp. 1 is the smallest of the three species of that genus noted and is characterized by a smooth, hyaline wall and a diameter of approximately 11-14 μm . The smooth wall of *Leiosphaeridia* sp. 2 is considerably larger in diameter (20-29 μm) and consistently light yellow in colour. *Leiosphaeridia* sp. 3 is of similar size to *Leiosphaeridia* sp. 2, but is hyaline and colourless. A simple split or pylome is present on some specimens.

Acanthomorph acritarchs (*i.e.*, spiny subspherical-to-spherical acritarchs), such as the various species of *Micrhystridium*, are very rare in the Quaternary portion of the core (Tab. 1), and those that do occur may be

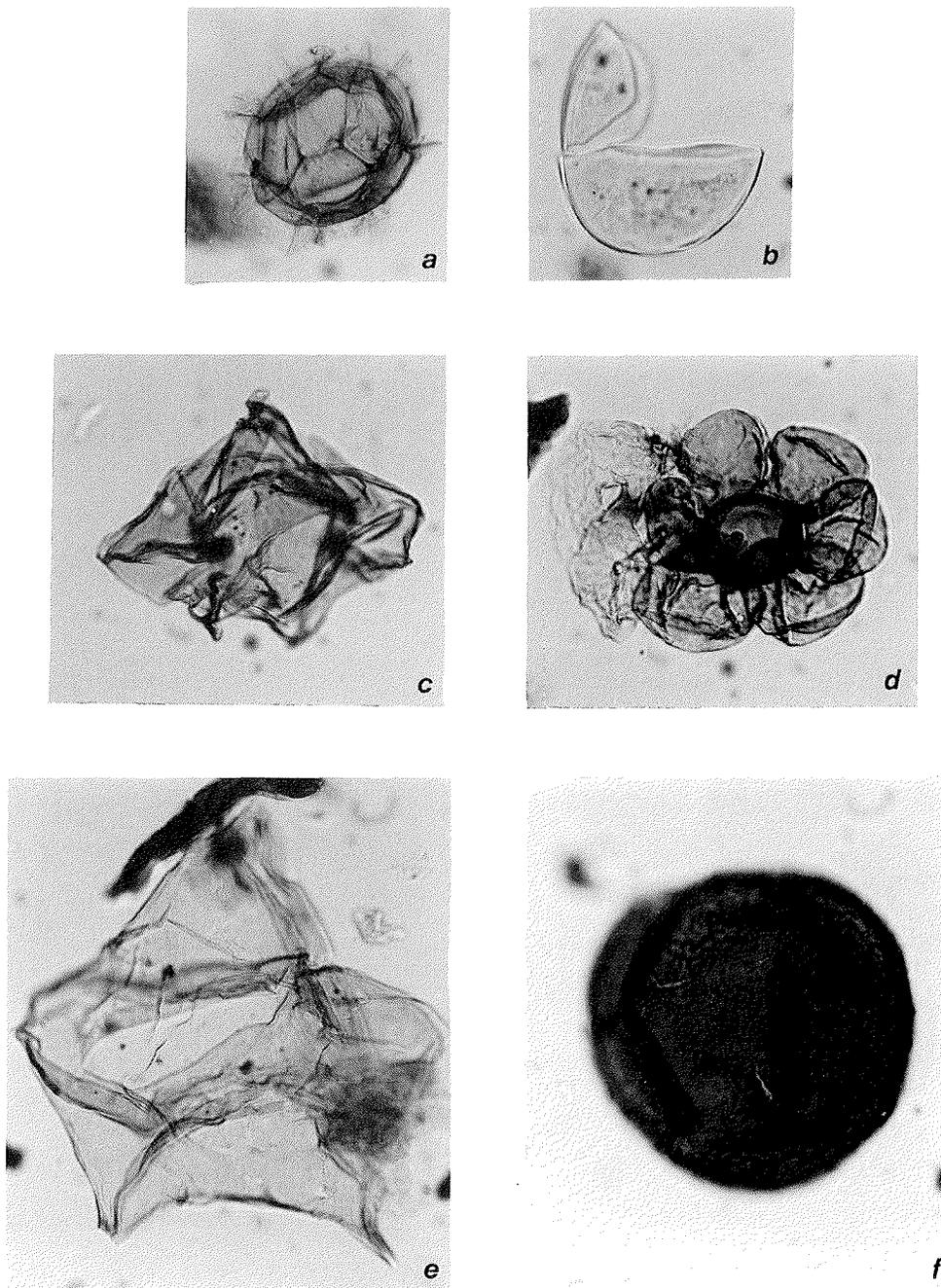


Fig. 3 - Selected marine palynomorphs from the CRP-1 core. Information provided, in order, includes: sample depth in meters below sea floor is indicated for the top of the sample interval; slide number; specimen coordinates; final magnification of photographic image.

a) *Cymatiosphaera* sp. 3 (sample depth 146.65 mbsf; slide number P43/1; specimen coordinates 108.4x15.2; final magnification 750X). b) *Sigmopollis* sp. (146.65 mbsf, P43/1, 112.5x9.5, 750X). c) *Lejeunecysta cowiei* Hannah et al. (this volume) (39.06 mbsf; P47/1; 113.5x4.4; 750x). d) Foraminiferal lining (146.65 mbsf, P43/1, 111.1x11.9, 750X). e) *Phelodinium cranwelliae* Hannah et al. (this volume) (146.65 mbsf, P43/1, 114.5x16.3, 750X). f) *Brigantedinium pynei* Hannah et al. (this volume) (146.65 mbsf, P43/1, 112.5x9.5, 750X).

reworked. Acritarch sp. 1 (Acritarch 9 of Cape Roberts Science Team, 1998) is small (20-30 μm diameter), lacks an aperture, and has a diffuse, perhaps fibrous wall, such as that seen in the dinocyst *Lanterosphaeridium lanosum*.

Sigmopollis sp. has a distinctive s-shaped or undulating cryptosuture that extends around the circumference of the light yellow cell, forming the aperture (Fig. 3b). *Leiosphaeridia* sp. 2 may be conspecific with *Sigmopollis* sp. because specimens are of the same size and colour, and generally co-occur in the core. However, *Leiosphaeridia*

sp. 2 never exhibits the sigmoid suture typical of *Sigmopollis* sp.

Foraminiferal linings (Fig. 4) and two new species of protoperidinioid dinocysts (Fig. 5a-f), considered to be *in situ*, were recovered from within the unique carbonate interval, lithostratigraphic Unit 3.1 (Fig. 2, sample depth 32.77 m). (A suite of samples from the carbonate unit is currently being studied in detail by JHW.) This very fossiliferous unit yielded abundant macrofossils (*e.g.*, pelycypods, gastropods, byozoans, *etc.*) and other microfossils, including a rich foraminiferal assemblage

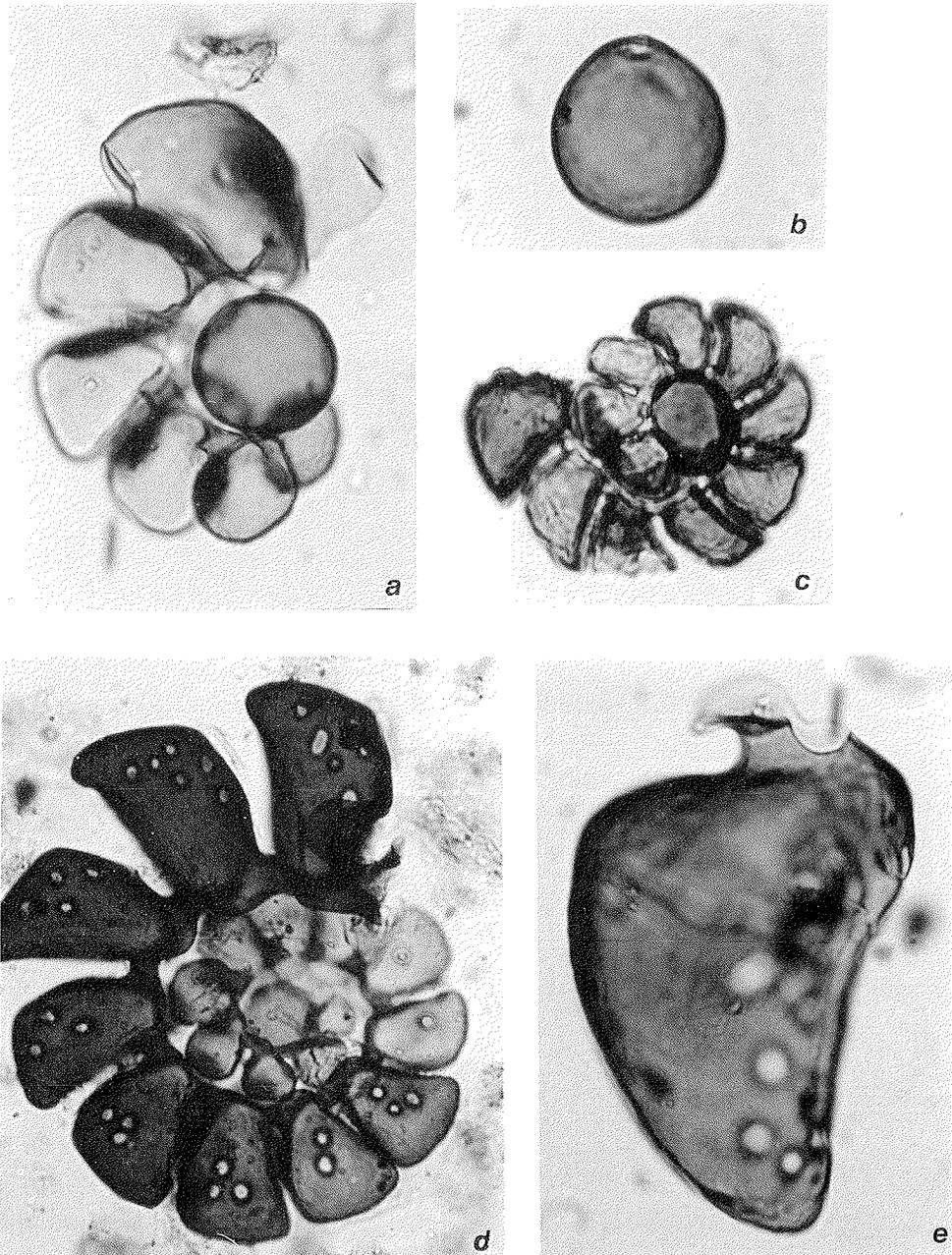


Fig. 4 - Selected foraminiferal linings from the unique carbonate rich Quaternary unit, Unit 3.1.

a) Trochospiral megalospheric foraminiferal test lining showing the large proloculum and first whorl of chambers. Reproduction was asexual. (31.0 mbsf; Slide 1; 95.7x5.1; 880X). b) Loose proloculum of a megalospheric foraminifer. These are very common in this sample. (31.0 mbsf; Slide 1; 80.0x14.0; 880X). c) Trochospiral microspheric foraminiferal test lining showing the small proloculum and one-and-one-quarter chamber whorls. Reproduction was sexual. (31.0 mbsf; Slide 1; 95.7x5.5; 880X). d) Trochospiral foraminiferal test lining showing at least two complete chamber whorls. The small proloculum indicates that this is the microspheric (sexual) foraminiferal generation. Note the lower magnification of the photograph of this very large specimen. (33.77 mbsf; Slide 1; 91.5x7.8m; 550X). e) Single chamber lining that has torn free from a very large foraminifer. (31.0 mbsf; Slide 1; 94.1x14.9; 880X).

(Webb & Strong, this volume) and rare nannofossils (Cape Roberts Science Team, 1998).

No recognizable dinoflagellate cysts were observed in the Quaternary samples during the initial core study (Cape Roberts Science Team, 1998). However, *Lejeunecysta fallax*, *Lejeunecysta cowiei* and *Brigantedinium pynei* have been noted at 36.06-36.07 mbsf during post-drilling detailed studies. These may be reworked; although the presence of *in situ* protoperidinioid cysts in the Quaternary carbonate unit suggests that the specimens of *Lejeunecysta cowiei* and *Brigantedinium pynei* may be *in situ* as well.

All palynomorph taxa that make their first downhole appearance in the Quaternary interval, except the new dinocyst species observed in the carbonate unit, range downhole into or throughout the lower Miocene interval (43.0-147.68 mbsf).

MIOCENE MARINE PALYNOMORPHS

Well preserved acritarchs, dinocysts and/or prasinophyte algae occur in all Miocene samples examined between 45.04 and 145.68 mbsf. Species diversity and

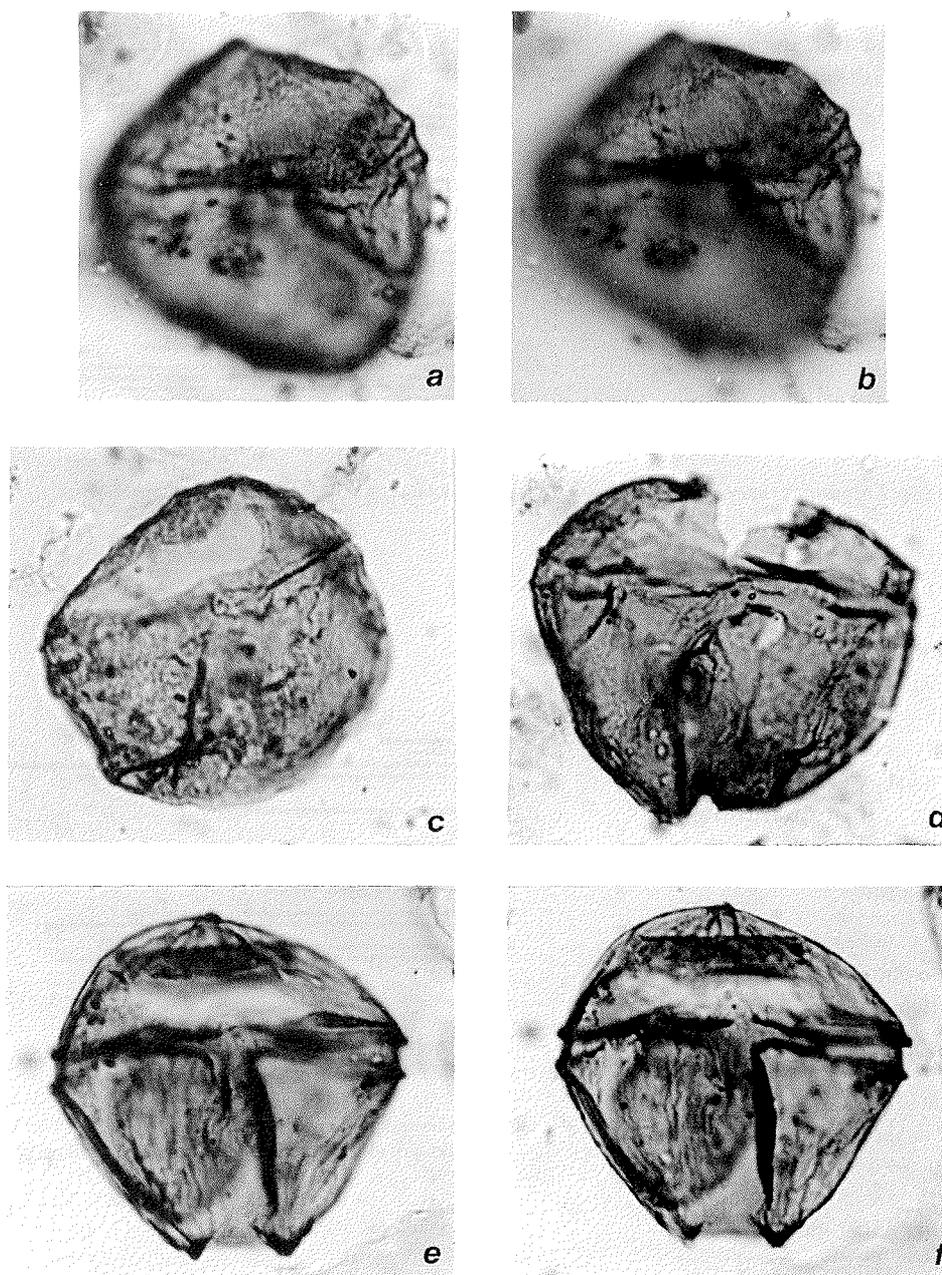


Fig. 5 - Protopteridinioid dinocysts from the carbonate-rich Quaternary unit, Unit 3.1. These are the first in-situ Quaternary dinocysts reported from Antarctica and are currently under study.

a & b) Dinocyst sp. A. (32.77 mbsf, Slide 1, 80.4x18.8, 880X). c) Dinocyst sp. A. (32.77 mbsf, Slide 1, 92.5x4.4, 880X). d) Dinocyst sp. A. (32.77 mbsf, Slide 1, 106.1x18.1, 880X). e & f) Dinocyst sp. B. (32.77 mbsf, Slide 1, 106.4x14.0, 880X).

specimen frequency varied throughout the core (Tab. 1). All marine palynomorphs are considered to be *in situ*, with the exception of rare reworked Palaeogene dinocysts (e.g., *Deflandrea antarctica*, *Vozzhennikovia apertura*, etc.) well known from previous Antarctic studies (Wilson, 1967, 1968; Wrenn & Hart, 1988).

Of the many different acritarchs encountered, 12 species were morphologically distinct enough to be included on the data table (Tab. 1). As in the Quaternary samples, two major acritarch groups are present: smooth, spherical-to-sub-spherical leiospheres, and a variety of acanthomorphs. As a group, acritarchs increase in abundance downsection, particularly in the lower 50 m of the core (Fig. 6). Similarly,

acritarch diversity increases downhole, but only to a depth of 99.10 mbsf. Below that depth, diversity decreases sharply because of the disappearance of acanthomorphs, which are almost exclusively restricted to the interval between 48.35 and 99.10 mbsf in the Miocene section (Fig. 7; Tab. 1). Acanthomorphs decrease slightly in abundance downsection within this interval, with abundance peaks at 48.35, 87.42 and 99.10 mbsf. All of the acanthomorph acritarchs can be assigned to the genus *Micrhystridium*. They are small spheres (all less than 35-40 μm in diameter), and a distinctive type of process characterizes each species (Hannah et al., this volume).

Leiospheres occur throughout the core and their

absolute abundance increases down core to such a degree that they more than compensate for the disappearance of acanthomorphs below 99.10 mbsf. Three species of *Leiosphaeridia* dominate all assemblages between that depth and the bottom of the core (Fig. 8).

A very low diversity dinocyst assemblage characterizes the Miocene sediments, beginning at 48.4 mbsf (Fig. 9; selected species are illustrated in Fig. 3). All are considered to be *in situ* and the assemblages exhibit a slight overall increase in abundance and diversity down core (Fig. 9, Tab.1).

Lower in the core, *Lejeunecysta cowiei* (Fig. 3c) and the cornucavate cyst *Phelodinium cranwelliae* (Fig. 3e), the largest of the protoperidinioid cysts recovered, become common. The latter genus is typically found in lower Palaeogene deposits. Below 87.42 mbsf, the thick, rugulate walled *Brigantedinium pynei* is commonly encountered (Fig. 3f). All of these dinocysts were produced by heterotrophic protoperidinioid dinoflagellates, the affinity of which is indicated by their archeopyle and brown colouration.

Many dinocysts and acritarchs exhibited a transparent, dark gray-to-black colour after initial sample processing. Similarly coloured algal spores were noted in DSDP Leg 94 (North Atlantic) core samples by Mudie (1986). We discovered that on the CRP-1 specimens this was a discolouration due to a coating of pyrite. However, the coating was so thin and the pyrite so fine grained that the specimens remained transparent. Pyrite spheres were not noted within the dinocysts, though loose framboidal pyrite was abundant in the sample residue. Treatment of the samples with nitric acid removed the pyrite coating from the protoperidinioid dinocysts and returned their distinctive light-to-dark brown colour.

This is an important observation. It would be easy to mistakenly attribute the dark colouration of the palynomorphs to thermal maturity of their organic wall, rather than to a thin pyrite coating on the wall surface. This could result in an erroneous estimation of the thermal maturity of the rock units that yielded such pyrite-coated palynomorphs. Within the context of the Cape Roberts Project, this could lead to mistaken interpretations regarding burial history of the units, or could suggest the existence of intrusive bodies close enough to the drillsite to heat the organics and impart a much higher thermal

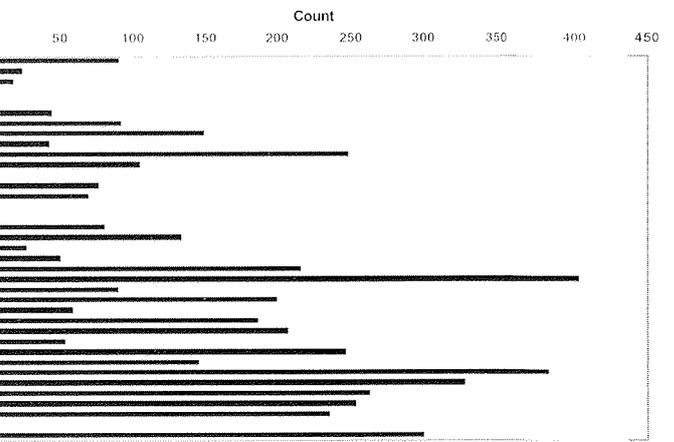


Fig. 6 - Count of the total acritarchs from the CRP-1 core.

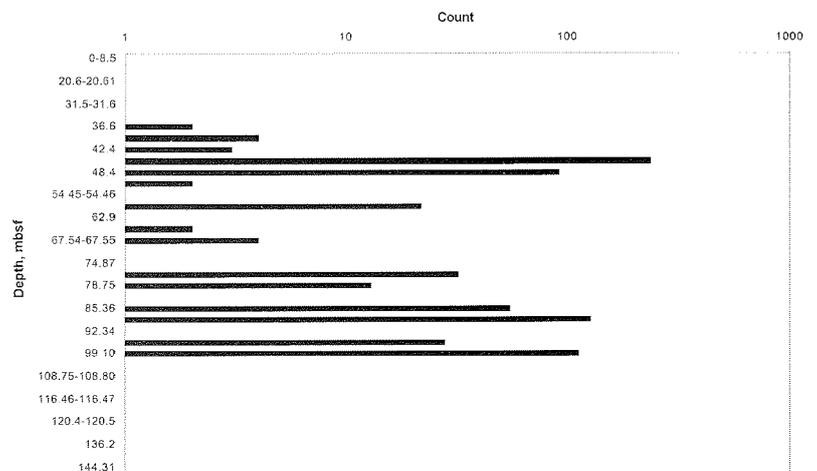


Fig. 7 - Total acanthomorph acritarchs, plus "1", from the CRP-1 core (the addition of one to the counts was necessary to plot the data on a logarithmic scale).

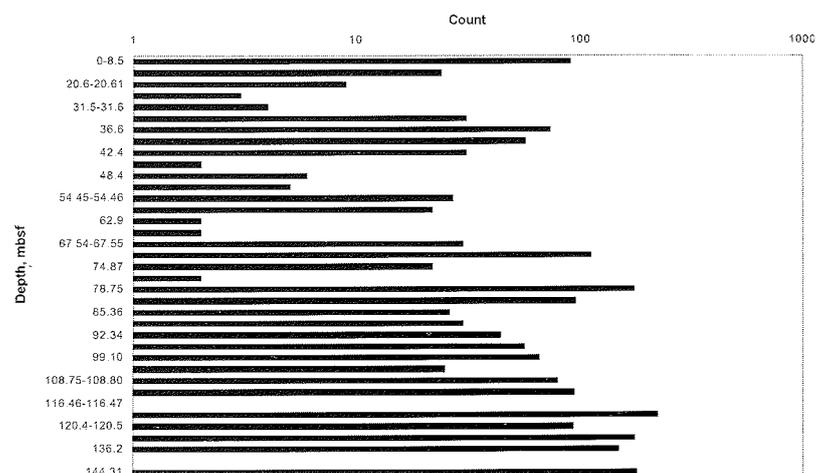


Fig. 8 - Total leiospheres in the CRP-1 core, plus "1" (the addition of one to the counts was necessary to plot the data on a logarithmic scale).

alteration colour than that resulting from simple burial. There are intrusive bodies at depth within 10 km of the drillsite (see Barrett, 1997 and Cape Roberts Science

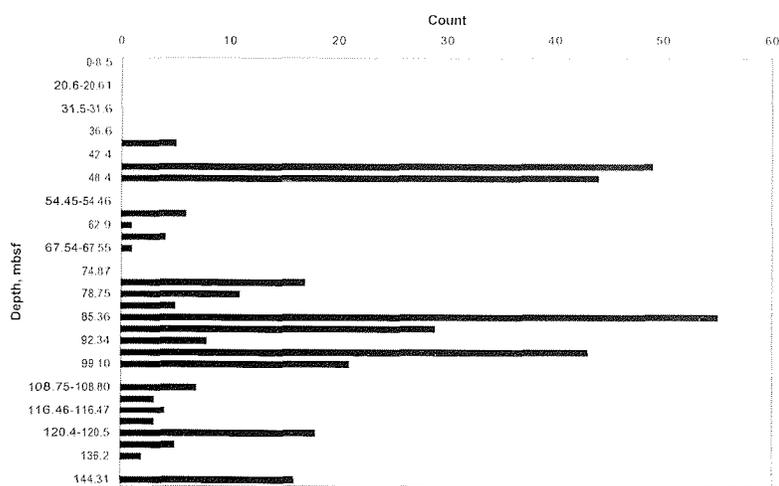


Fig. 9 - Total *in situ* dinocysts plotted on a linear scale.

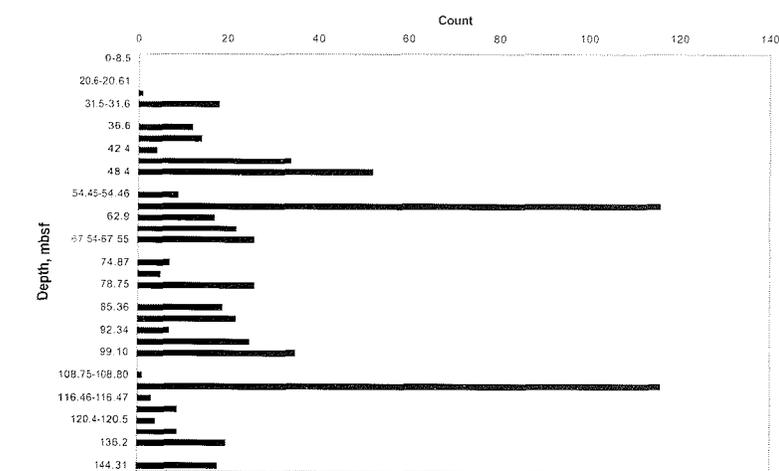


Fig. 10 - Chart showing the distribution of foraminiferal linings in the CRP-1 core.

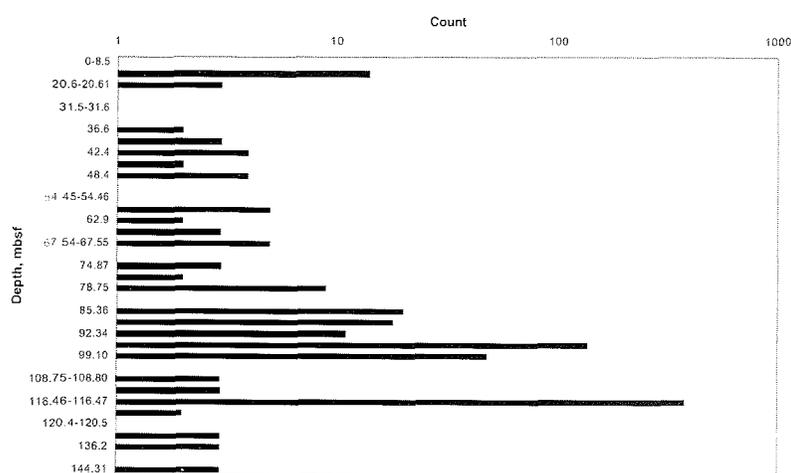


Fig. 11 - Total prasinophytes in the CRP-1 core, plus "1" (the addition of one to the counts was necessary to plot the data on a logarithmic scale).

cycles during which they increase from low to high abundance, reaching highs at 58.43 and 112.44 mbsf (Fig. 10). The top of a third cycle is suggested by the data collected from the bottom of the core. The significance of these apparent cycles, if any, is unknown.

Three species of *Cymatiosphaera* and one each of *Pterospermella* and *Tasmanites* (probably reworked) occur in the core (Tab. 1). Prasinophytes increase down section, reaching peaks at 96.37 and 116.46 mbsf (Fig. 11). Below the latter depth, they are rarely encountered down to the base of the core. The most frequently occurring prasinophyte in the Miocene samples is *Cymatiosphaera* sp. 3, a large form with a brown central body having membranes up to 9 μ m high (Fig. 3a). *Cymatiosphaera* sp. 2 occurs most consistently and abundantly in Miocene samples below 78.15 mbsf (rare specimens in Samples 36.6, 20.6 and 20.04 mbsf in the Quaternary section may be reworked).

PREVIOUS WORK

ANTARCTIC DINOFLAGELLATE CYSTS AND MOTILE DINOFLAGELLATES

Fossil Dinocysts

The Antarctic dinocyst record is biased and continues to be of limited extent compared to that of the modern day lower latitudes. This is true in spite of the significant discoveries that have been made during the past 10 years (e.g., Askin, 1988; Wrenn & Hart, 1988; Coccozza & Clarke, 1992; Dolding, 1992; Keating, 1992; Keating et al., 1992; Smith, 1992; Snape, 1992; Sumner, 1992; Wood & Askin, 1992). Outcrops, particularly of marine sediments, are rare in ice-covered Antarctica and relatively few holes have been drilled on or around the continent. The few productive outcrops that do exist are primarily Late Cretaceous and early Cainozoic in age, thus introducing an age bias in a record already biased by limited exposures.

There is one final bias of the dinocyst record, in Antarctica, as well as elsewhere, that should be noted. The majority of fossil dinoflagellates are organic-walled cysts, not the remains of the motile stage. Most

Team, 1998) so this is not as irrelevant as might first appear.

Foraminiferal test linings are rare to common in most samples. Their numbers vary through two abundance

motile dinoflagellates are covered either by a cellulosic theca or an ephemeral membrane, neither of which is preserved in the fossil record; only the organic walled cysts are resistant enough to be fossilized. Few of the

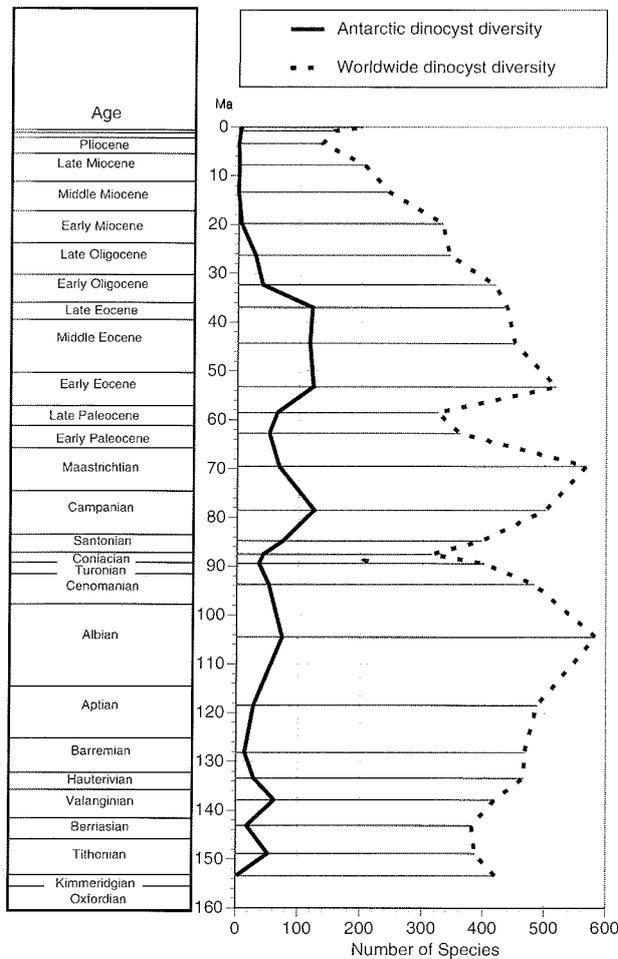


Fig. 12 - Dinocyst diversity in the Antarctic fossil record (solid black line) compared to that of the world-wide dinocyst record. The Antarctic plot is based on a PALYNODATA search that retrieved data from the 91 Antarctic dinocyst papers in its database. The world-wide dinocysts curve is adapted from MacRae et al. (1996).

approximately 2 200 extant dinoflagellate species are known to produce preservable cysts, perhaps only 10% (Dale, 1976). This is assumed to have been true in the past. Thus, the fossil dinocyst record provides a very limited view of the diversity and abundance of the motile dinoflagellate population that existed at the time the cysts were formed. Consequently, it is hazardous to speculate on paleoproductivity based solely on fossil dinocyst abundance or diversity. All that can be discussed are the variations in the cyst producing species, which, as noted above, may be as little as 10% of the species present in the dinoflagellate population. This aspect and others were discussed more completely and more eloquently long ago by Evitt (1981) in his cautionary note on the fossil record of dinoflagellate cysts.

Figure 12 shows that dinocyst diversity has changed markedly in Antarctica and worldwide through time. The Antarctic dinocyst curve is based on data generated from PALYNODATA, a computer database containing the palynologic data from approximately 20 000 palynologic publications (see MacRae et al., 1996, for additional information on PALYNODATA). Data from all papers in PALYNODATA (91) published on Antarctic Mesozoic and Cainozoic dinocysts through 1997 plus the Miocene

Tab. 2 - Antarctic and worldwide dinocyst species diversity data that is plotted in figure 13.

Age	MYA. mid-range date	Dinocyst Diversity	
		Antarctic	Worldwide
Holocene	0.1	5	200
Pleistocene	0.82	3	155
Pliocene	3.42	0	136
Late Miocene	7.8	1	204
Middle Miocene	13.35	0	244
Early Miocene	19.80	5	332
Late Oligocene	26.30	28	
Early Oligocene	32.35	40	418
Late Eocene	37	121	438
Middle Eocene	44.3	117	451
Early Eocene	53.25	123	518
Late Palaeocene	58.5	65	325
Early Palaeocene	62.75	52	361
Maastrichtian	69.5	68	568
Campanian	78.5	125	501
Santonian	84.8	75	397
Coniacian	87.55	43	315
Turonian	89.45	36	401
Cenomanian	93.7	52	483
Albian	104.5	74	584
Aptian	118.5	28	488
Barremian	128.15	14	468
Hauterivian	133.4	29	466
Valanginian	137.85	62	419
Berriasian	143.15	18	382
Tithonian	148.85	52	387
Kimmeridgian	153.4	2	420

Note: Antarctic data is derived from a search of the PALYNODATA database for all dinocyst occurrences reported from Antarctica. Worldwide data is from MacRae et al. (1996). The chronological scheme is that of Harland et al. (1990).

data from the CRP-1 core were synthesized to generate the Antarctic dinocyst distribution curve. The plot is based on the reported occurrence of all formally described species from Antarctica.

The other curve on figure 12 shows dinocyst species diversity through time on a worldwide scale. This curve is based on data published by MacRae et al. (1996). The tabulated data for both curves are shown on table 2.

Nomenclature of taxa reported in the Antarctic literature was standardized in accordance with that listed in Lentin & Williams (1993), and synonymous taxa were combined under the currently accepted name. For taxa reported only at the generic level, the genus was counted as one species and included as such in the plot. No reworked taxa, or those reported as "cf." or "aff." were included in the tabulation. Some of these tentatively identified taxa eventually may be described as new species when more specimens are available for study. Thus, the Antarctic curve on the plot (Fig. 12) is conservative and is based only on well-described and firmly identified taxa. Species were tabulated by geological age and the species diversity for each geological age is plotted in the approximate centre of the appropriate time interval on figure 12.

The PALYNODATA search indicated that there are only two Late Triassic taxa reported from Antarctic sediments, but these are not included on figure 12. The next oldest dinocyst species reported from Antarctica are from Late Jurassic units, though even these are few in number. Dinocyst diversity remained low through the middle Cretaceous, but then increased, reaching the Mesozoic maximum of 125 species during the Campanian.

A sharp decline in dinocyst diversity occurred during the Maastrichtian (63 species), and only 20 species safely crossed the Maastrichtian-Palaeocene boundary. Based on a detailed study of K-T dinocysts on Seymour Island, Askin & Jacobson (1996) concluded that the decline was not sudden at the boundary, but gradual over much of the Maastrichtian.

Dinocyst diversity began to rebound during the Danian (52 species) and rose to 65 species during the late Palaeocene (Thanetian). Based on published records, the Eocene was the Cainozoic "golden age" of dinocysts in Antarctica. Species diversity exceeded 100 species during the entire Eocene.

Dinocyst diversity decreased by two-thirds across the Eocene/Oligocene boundary, from 121 species to a mere 40 species in the early Oligocene. This was an even greater decline than that at the close of the Mesozoic, and set the trend that was to continue, apparently up to the present day. Only 28 species of dinocysts have been reported from upper Oligocene deposits.

There are few reports of dinocysts from Miocene deposits of Antarctica. One species, *Bitectatodinium tepikense* was recovered from outcrops on James Ross Island, Antarctic Peninsula, that is interpreted to be of Miocene age (Pirrie et al., 1997), though the dating of the units does not appear to be firm. Reputed Miocene dinocysts have been reported from surface sediments of the Bransfield Strait in West Antarctica (Byun et al., 1992). However, all are considered by McMinn (1995) to be reworked Late Cretaceous and Palaeogene taxa. We concur with his evaluation of these assemblages.

The early Miocene and Quaternary dinocyst species in the CRP-1 core occur in units independently and firmly dated by diatom, isotope and palaeomagnetic studies (Cape Roberts Science Team, 1998; Bohaty, this volume; Harwood et al., this volume; Lavelle, this volume; Roberts et al., this volume). Though it is agreed that the older part of the section is early Miocene in age, debate continues regarding exactly which part of the lower Miocene was cored. This debate notwithstanding, the CRP-1 material represents the only Miocene and Quaternary dinocysts from Antarctica whose age is as yet independently and firmly determined.

Reports of modern cysts are as sparse as the Neogene record. To date six extant species are known to produce cysts, including five thecate heterotrophic dinoflagellates (Balech, 1973; Marrett & de Vernal, 1997) and one athecate, autotrophic dinoflagellate (Stoecher, et al., 1991; Buck et al., 1992). Only the four species reported from the offshore Indian Ocean sector of Antarctica by Marrett & de Vernal, 1997) are known to be fossilizable. They are assumed to be *in situ*, though no independent dating of the surface samples was conducted to confirm their Holocene age. Balech (1973) included a drawing of *Protoperidinium antarcticum* showing a cyst inside its theca. Thus far, such cysts have not been reported from Holocene Antarctic sediments.

The general trend noted in figure 12 is a decrease in dinocyst producing species upsection, from the middle Cretaceous and Palaeogene to the present. The high point of diversity during the Eocene may merely reflect the

unique and diverse dinocyst assemblages recovered from McMurdo Sound erratics (Wilson, 1967, 1968), the extensive outcrops on Seymour Island (Wrenn & Hart, 1988; Cocozza & Clarke, 1992) and Ocean Drilling Project (ODP) cores from the Weddell Sea (Mohr, 1990b). Mohr (1990b) notes that the moderately diverse Eocene assemblages (approximately 15-20 species) reported from at ODP 696 in the Weddell Sea all but disappear by late early Oligocene time. The decline is evident in the nearby ODP Site 693 core where assemblages consist only of two species in upper lower Oligocene sediments from the Antarctic continental shelf. The marked dinocyst decline during the Oligocene probably resulted from the major cooling events in the Southern and world oceans at the Eocene/Oligocene boundary and again during the late early Oligocene. Cooling was apparently caused by the development of deep ocean circulation between the newly separated South America and Antarctica and the advent of the Circum-Polar Current (Kennett, 1978; Elliot, 1985).

However, it is interesting to note that the diversity record of the modest Antarctic database for middle Cretaceous-Palaeogene dinocysts closely resembles that of the much more robust worldwide record of dinocyst species covering the same time interval (Fig. 12). The Antarctic species diversity is much lower than is worldwide diversity, but the distribution curves are similar in shape. The Antarctic record thus mimics the worldwide record for this time interval, in spite of the inherent biases of the Antarctic (*i.e.*, scarcity of outcrops of marine sediments, and the restricted ages represented in outcrops and cores studied).

The distribution also helps explain the scarcity of the assemblages and paucity of taxa recovered from the CRP-1 core. Diversity of cyst-producing dinoflagellates declined markedly not only in Antarctica, but worldwide, after the Eocene "golden age" of dinocysts. However, the drop was apparently greater and faster in Antarctica than at lower latitudes. The post-Eocene decline in diversity became a crash in the Neogene. This crash may be an artifact due to the relatively little dinocyst research conducted on post-Eocene sediments in Antarctica thus far. The CRP-1 assemblages demonstrate that, contrary to earlier beliefs, cyst-producing dinoflagellates were present in Antarctic seas during Neogene-Quaternary time and that Antarctic sediments of those ages are worth investigating for dinocysts.

Extant Dinoflagellates

Reports of extant, motile dinoflagellates are much more extensive than those of extant dinocysts. A partial survey of the Antarctic biologic and ecologic literature (Stoecher et al., 1991; Buck et al., 1992; Garrison, 1991) showed that more than 63 formally described motile dinoflagellate species have been reported from Antarctic waters (Tab. 3). These are all endemic taxa, though not taxa necessarily restricted to waters south of the Antarctic Convergence (Polar Front). Other dinoflagellates, "visitors" from northern waters, do make periodic incursions south of that oceanographic boundary, but they are not permanent members of the high-latitude dinoflagellate community (Balech, 1975). Fifty-two thecate

Tab. 3 - Antarctic Holocene dinoflagellates and dinocysts reported in the literature.

Motile Dinoflagellates*		Extant Dinocysts	
Thecate Dinoflagellates	Athebate Dinoflagellates		
<i>Protoperidinium</i>	<i>Dinophysis</i>	<i>Amphidinium</i>	Cysts of Thecate Dinoflagellates
<i>adeliense</i>	<i>antarctica</i>	<i>hadai</i>	** <i>Protoperidinium antarcticum</i>
<i>affine</i>	<i>cornuta</i>	sp.	** <i>Impagidinium pallidum</i>
<i>antarcticum</i>	<i>contracta</i>	<i>Gymnodinium</i>	** <i>Brigantedinium</i> spp.
<i>applanatum</i>	<i>meteori</i>	<i>baccatum</i>	** <i>Selenopemphix antarcticum</i>
<i>archiovatum</i>	<i>punctata</i>	aff. g. <i>diploconus</i>	
<i>areolatum</i>	<i>tenuivelata</i>	<i>flavum</i>	
<i>bellulum</i>	<i>tuberculata</i>	<i>frigidum</i>	
<i>bipatens</i>	spp.	<i>guttula</i>	
cf. <i>crassipes</i>	<i>Diplopeltopsis</i>	<i>minor</i>	Cysts of Athebate Dinoflagellates
<i>charcoti</i>	<i>granulosa</i>	<i>modestum</i>	Gymnodinioid cyst A
<i>concauum</i>	<i>minor</i>	<i>soyai</i>	Stoecker, 1993
<i>cruciferum</i>	<i>Perlata</i>	spp.	Gymnodinioid cyst A
<i>curtum</i>	spp.	<i>Gyrodinium</i>	Buck et al., 1992
<i>defectum</i>		<i>glaciale</i>	
<i>elegantissimum</i>	<i>Heteroschisma</i>	<i>lachryma</i>	
<i>glyopterum</i>	<i>subantarctica</i>	spp.	Visitors to Antarctic waters:
<i>incertum</i>	<i>Oxytoxum</i>	<i>rhabdomante</i>	** <i>Dallea chathamense</i>
<i>incognitum</i>	<i>criophilum</i>		** <i>Impagidinium aculeatum</i>
<i>latistriatum</i>	<i>Podolampus</i>	Undescribed taxa	** <i>Impagidinium sphaericum</i>
<i>macrapicatum</i>	<i>antarctica</i>	athebate dinoflagellate	** <i>Nematosphaeropsis labyrinthus</i>
<i>mangini</i>	<i>Prorocentrum</i>	Buck et al., 1990	** <i>Pyxidiniopsis reticulata</i>
<i>mediocre</i>	<i>antarcticum</i>	<i>Diplopeltopsis</i> spp.	
<i>melo</i>	sp. sensu Balech &	Archer et al., 1996	
<i>metanatum</i>	El-Sayed, 1965	<i>Gyrodinium</i> sp. 1	
<i>nanum</i>	spp.	Archer et al., 1996	
<i>parcum</i>		<i>Gyrodinium</i> sp. 2	
<i>parvicollum</i>		Archer et al., 1996	
<i>penitum</i>		<i>Gymnodinium</i> sp.	
<i>pseudoantarcticum</i>		Bjornsen & Kuparinen, 1991	
<i>radius</i>		Gymnodinioid cyst A	
<i>raphanum</i>		Stoecker, 1993	
<i>rosaceum</i>		Buck et al., 1992	
<i>saltans</i>		<i>Polykrikos</i> sp. Stoecker 1993	
<i>sphaeroidium</i>		<i>Protoperidinium</i> sp.1	
<i>thulesense</i>		Archer et al., 1996	
<i>turbinatum</i>		<i>Protoperidinium</i> sp.2	
<i>unipes</i>		Archer et al., 1996	
<i>variegatum</i>		<i>Protoperidinium</i> sp.3	
		Archer et al., 1996	

Note: * primarily from Balech (1975); ** cited in Marret & de Vernal (1997).

and 11 athebate dinoflagellate species are listed in table 3. Another 15 clearly distinct dinoflagellate taxa have been reported in the biologic literature using informal taxonomy and await formal description (Archer et al., 1996; Buck et al., 1990, 1992; Bjornsen & Kuparinen, 1991; Stoecker et al., 1991, 1993). Undoubtedly, there are more that have been reported in the extensive biologic literature than we note here, and probably there are many more dinoflagellates in Antarctic waters that have yet to be found and studied. Of significance here is that of the nearly 80 motile species noted above, only five (less than 10%) are known to produce cysts. Head (1996) notes that 13-16% of known extant dinoflagellates produce cysts, though not necessarily all of these cysts are amenable to fossilization. If this percentage, or even the earlier estimate of 10% (Dale, 1976), is correct and if it holds true for the southern high latitudes, there must be more Holocene cyst species to be found in modern Antarctic sediments. This is true even if not all of the modern cyst types are amenable to fossilization.

PRASINOPHYTES IN ANTARCTICA

Prasinophytes are commonly reported to be associated with distinctive water-column features. These usually include low temperature, enhanced productivity and a stratified water column exhibiting brackish or low-salinity surface waters overlying low oxygen to anoxic bottom waters (Tyson, 1987). A coastal setting is often cited in the literature for their occurrence, but prasinophytes occur in pelagic, open-marine, brackish, and fresh waters as well as in saline lakes (Tyson, 1995; van der Hoff et al., 1989).

Prasinophytes may produce scale covered cysts (Tappan, 1980) or a thick walled, non-motile pelagic phycoma (Parke et al., 1978). Unlike a cyst, a phycoma continues to grow, up to 20 times its initial size, during the non-motile phase of the life cycle (Parke et al., 1978; Wiebe et al., 1974). It is the organic walled phycoma that is preserved in the fossil record. *Tasmanites*, *Cymatiosphaera*, and *Pterospermella* are examples of such fossils described in the palynologic literature.

Tab. 4 - Reports of fossil *Cymatiosphaera* from Antarctica.

<i>Cymatiosphaera</i>	Age	Location	Cited by
<i>costada</i>	Late Campanian	Antarctic Peninsula	Smith, 1992
<i>nekouda</i>	Late Campanian	Antarctic Peninsula	Smith, 1992
<i>pachytheca</i>	Valanginian-Hauterivian	Weddell Sea	Mohr, 1990a
sp.	Eocene (?reworked)	RISP J-9, Ross Sea	Wrenn, 1981
sp.	Middle Miocene-Late Pleistocene	RISP J-9, Ross Sea	Wrenn & Beckman, 1981
sp.	Late Paleocene-Eocene	Antarctic Peninsula	Wrenn & Hart, 1988
sp.	Late Campanian	Antarctic Peninsula	Dolding, 1992
sp.	Santonian-Early Campanian	Antarctic Peninsula	Keating, 1992
<i>wetzellii</i>	Late Campanian	Antarctic Peninsula	Smith, 1992
<i>wetzellii</i>	Late Campanian	Antarctic Peninsula	Dolding, 1992

Extant prasinophytes are widespread in Antarctic waters and a massive bloom was observed in the Gerlach Strait off the west coast of the Antarctic Peninsula (Bird & Karl, 1991). Fossil prasinophytes occur most abundantly in fine-grained, organic-rich sediments (Tyson, 1995). Abundant amorphous matter, iron pyrite and laminated sediments suggest deposition below wave base under reducing conditions in oxygen-depleted or anoxic waters (Tyson, 1987). Modern prasinophytes are common in high latitudes, though it is uncertain if all cold-water forms produce phycoma (Manton, 1977). The presence of *Cymatiosphaera* spp. in the CRP-1 core indicates that, at least in the past, they did produce phycoma in Antarctica. *Cymatiosphaera* has been reported infrequently from Antarctica (Tab. 4) and all reports have been from pre-Holocene sediments. Most occurrences are documented from West Antarctic outcrops (Wrenn & Hart, 1988; Smith, 1992; Dolding, 1992; Keating, 1992) or offshore cores (Mohr, 1990a). There are only two previous reports of fossil prasinophytes from the Ross Sea sector (Wrenn, 1981; Wrenn & Beckman, 1981).

SEA-ICE ALGAL COMMUNITIES AND PALYNOLOGY

Antarctic Sea-Ice Communities

Antarctic sea-ice is riddled with a complex mixture of brine channels, brine pockets and pores, all of which can be habitats for microorganisms (Spindler et al., 1990). The existence of sea-ice communities has been known since the 1840's, but detailed studies of the communities were not begun until the 1960's (Knox, 1994). The rapidly expanding literature on the composition, physiology and trophic structures of Antarctic sea-ice microbial communities is of considerable importance to the interpretation of post-Palaeogene marine palynomorph assemblages, particularly dinocysts from the high latitudes.

It was demonstrated in the Weddell Sea during the early 1980s that the traditional view of a very abbreviated Antarctic food chain was not correct. Rather than just a three-step chain consisting of diatoms being consumed by krill that are, in turn, consumed by marine mammals, a complex food web was recognized (Buck & Garrison, 1983). The complex food web consists of nanoplankton and microplankton primary producers and consumers as well as considerable quantities of bacteria at the base of the structure, with krill, fish and mammals towards the top. In fact, the abundance of bacteria in the waters of McMurdo Sound led Lessard & Rivkin (1986) to conclude that the

complex food web there was based on bacterivory, rather than herbivory, by micro- and macroplankton.

It was also recognized that significant primary production occurs at the sea-ice margin (Garrison et al., 1987) as well as within the sea-ice column (Garrison, 1991; Knox, 1994). More than 200 taxa have been reported to live in association with sea-ice (Garrison, 1991), and these comprise different communities depending on whether they live on, in, or at the bottom of the sea-ice (Knox, 1994). When the sea-ice breaks up and melts, the microalgae are released into the water column, becoming a rich source of nutrients for heterotrophs, including protoperidinioid dinoflagellates. This downwelling enriches surface waters with nutrients from above, rather than from below, as is the case with upwelling. Vast plankton blooms are initiated by downwelling along the melting annual ice margin and within the dispersing pack ice during the Austral summer.

Most sea-ice microbial studies have dealt with diatom communities. Diatom-dominated communities are most common and abundant on the bottom and in the interior of the sea-ice column. In contrast, dinoflagellate- and ciliate-dominated microbial communities occur in brine channels and pockets of the land-fast ice column in McMurdo Sound (Stoecker et al., 1991) as well as in surface layer communities of pack ice (Stoecker et al., 1993). The ice surface community is dominated by an autotrophic athecate dinoflagellate that produces small (<15 µm diameter) chorate cysts. These dinoflagellates are unusual in that they are active and excyst in waters colder (-8°C) and more saline (129 psu) than environmental limiting conditions commonly associated with the upper sea ice communities (Stoecker et al., 1997). The cysts seem to be adapted to overwintering in sea ice and to dispersal as the sea ice decays in spring (Stoecker et al., 1998). This small cyst-forming gymnodinioid dinoflagellate is widespread in McMurdo Sound (Stoecker et al., 1992), the Weddell Sea (Buck et al., 1992), and Ellis Fjord, East Antarctica (McMinn, 1995). The Ross Sea sea-ice brine community also contains significant numbers of large (>20 µm) heterotrophic dinoflagellates, including *Gymnodinium* sp. and *Polykrikos* sp., with occasional species of *Gyrodinium* and *Protoperidinium* occurring in brine pockets (Stoecker et al., 1993).

Arctic Ocean Sea-Ice Communities

Acritarchs, particularly leiospheres, are a major component of some Arctic sea-ice algal assemblages and

in Quaternary marine deposits. Studies of sea-ice margins on the Beaufort and Barents shelves showed that *Leiosphaeridia* spp. were most abundant at the contact margin between the pack ice and the seasonal ice. Here, they constituted 20-70% of a plankton assemblage that also included dinocysts, archaeomonads and prasinophytes. Other acritarchs, such as *Cyclopsiella*, *Halodinium*, *Beringiella*, and *Sigmopollis* are commonly reported from these settings, as well as from Arctic estuaries (Mudie, 1992).

Prasinophycean algae, particularly *Cymatiosphaera*, are abundant in the normal-to-low salinity, nutrient-rich arctic waters, such as those that upwell off northeastern Greenland and in north Baffin Bay (Mudie, 1992). *Pterosperma* sp. occurs in low salinity, stratified water layers in arctic fjords, though they are more commonly found in oceanic water masses (Mudie, 1992).

Similar trends have been reported for protoperidinioid marine dinocysts that dominate Neogene-Holocene cold water arctic assemblages. Protoperidinioids are heterotrophic, non-photosynthetic dinoflagellates (Fensome et al., 1993) that generally produce brown to dark brown cysts. Quaternary-Holocene glacial sediments in ODP 646, in the Labrador Sea, were dominated by cysts of *Brigantedinium* (de Vernal & Mudie, 1989), a typical protoperidinioid cyst of the region, as were Holocene glaciomarine sediments in Norway, arctic Canada and Svalbard (Dale, 1996). Protoperidinioid assemblages recovered from Miocene deposits of ODP 647 cores from Baffin Bay were well developed in settings interpreted to have been influenced by 1) high river discharge, 2) falling sea level, 3) cold currents, or 4) ice cover (Head et al. 1989a, 1989b).

Mudie (1986) reported that dark coloured acritarchs and dinocysts are common in cold waters and in the Arctic. Dale (1996) observed that protoperidinioid heterotrophs are typical of cold Arctic waters and are dominant in upwelling areas due to high nutrient input that supports a rich phytoplankton community, the prey of the heterotrophs. Others also have noted the dominance of heterotrophic protoperidinioids in polar regions (e.g. Balech, 1973) and that they are limited by light and salinity (Taylor, 1987; Mudie, 1992), rather than by a shortage of nutrients as is often the case with photosynthetic dinoflagellates in other areas.

Overall, these reports indicate that acritarchs, prasinophytes and protoperidinioid dinocysts are abundant today in Arctic Ocean sediments deposited under nutrient-rich, cold waters of normal to slightly low salinity, often in association with pack and seasonal sea-ice. This has been documented in widely separated areas of the Arctic Ocean and adjoining seas. They have been used there as ice-edge indicators.

DISCUSSION

The CRP-1 marine palynomorphs were produced primarily by planktonic motile organisms. Some were autotrophic (e.g. the prasinophytes and perhaps some of the acanthomorphs), whereas others were heterotrophs (e.g. the protoperidinioid dinoflagellates) that preyed on

the autotrophs and other heterotrophs. Together these plankton indicate the existence of open-water conditions or at least very thin ice, either continuously or seasonally, because the autotrophs need sunlight to carry on photosynthesis.

This interpretation is supported by data from the Arctic Ocean and other northern high-latitude sites. In those areas the prasinophytes, protoperidinioid dinocysts, and acritarchs (especially the leiospheres) are most abundant adjacent to sea-ice margins and within the disintegrating pack ice during the spring thaw (Mudie, 1992; Mudie & Harland, 1996).

Protoperidinioids seem to inhabit the water column in Antarctica just below the sea-ice, hunting microbes living at or on the ice/water interface. During seasonal breakup of sea-ice, they ascend the brine channels looking for prey including diatoms, ciliates, other dinoflagellates, bacteria, and probably any other microbes encountered (Stoecker et al., 1993). It is possible that the protoperidinioid cysts recovered from the core were those of dinoflagellates that occupied a similar niche and had similar habits during the Miocene.

Acanthomorphs are present in assemblages both from the Arctic and the Antarctic. Those from the CRP-1 core are very similar to dinocysts produced by extant autotrophic sea-ice dinoflagellates. These dinoflagellates are an important part of upper sea-ice communities dominated by flagellates. If the chorate cysts that they produce can be fossilized, they could be used as indicators of seasonal sea ice and sea-ice microbe communities (Stoecker et al., 1991).

We speculate here that some, perhaps all, of the CRP-1 acanthomorph acritarchs were produced by similar sea-ice dinoflagellates during the Miocene. If this is correct, then they can be used as indicators of seasonal sea-ice and sea-ice alga and flagellate communities. We may never be able to determine if the acanthomorphs are cysts of sea-ice dinoflagellates. However, other types of data may permit us to evaluate their utility as sea-ice indicators. Based on the above discussion, we believe that the Antarctic marine palynomorph assemblages first described from the CRP-1 core may prove to be useful sea-ice margin and pack ice indicators in post-Oligocene sediments of Antarctica.

The CRP-1 core can be divided informally into three sections based on the distribution of marine palynomorphs: 0-44 mbsf (Quaternary), ~44-99 mbsf (upper part of the lower Miocene section), and ~99-145 mbsf (lower part of the lower Miocene section). Marine palynomorphs of all types are least abundant in the Quaternary (0-43 mbsf) section of the core. We speculate that this indicates sea-surface conditions were not favorable for palynomorph producing plankton or for sea-ice communities. Such conditions might include perpetual ice cover, grounded ice shelves, high turbidity due to high sedimentation rates, or low sea level during glacial events. This interpretation is in accord with that proposed for Quaternary deposition based on sediment studies (Cape Roberts Science Team, 1998), which indicated intense grounding and high sedimentation rates and possible terrestrial conditions at certain times during the deposition of this unit.

The main exception to this scenario is Unit 3.1, the carbonate unit. Clearly this was characterized by unique environmental and depositional conditions. We have completed studies on too few samples from this unit (though protoperidinioid dinocysts were noted at 32.77 mbsf) to comment on assemblages or conditions this unit represents. Webb & Strong (this volume) have completed a very detailed study of this unit and present some interesting conclusions. The Cape Roberts Science Team (1998) concluded that the unit was deposited during an interglacial when most glaciers had melted, or were considerably reduced, in the nearby Transantarctic Mountains and few icebergs crossed the region.

The upper portion of the lower Miocene section (43.55-99.10 mbsf) contains abundant acanthomorphs, leiospheres, and prasinophytes, as well as less abundant protoperidinioid dinocysts. These indicate conditions favorable for the development of planktonic and sea-ice communities, assuming, of course, that these acanthomorphs are sea-ice dinocysts. Seasonal sea-ice, periodic melting and ice breakup, and extensive open water are indicated. It is interesting to note the much greater numbers of acanthomorphs (autotrophic dinocysts?) than protoperidinioid cysts (heterotrophic dinocysts). Could this reflect some type of predator: prey ratio? The sedimentary record indicates that this was a time of intense ice grounding and high sedimentation rates alternating with periods of open water (Cape Roberts Science Team, 1998).

The lower portion of the lower Miocene section (99.10-147.69 mbsf) is dominated by planktonic taxa, especially leiospheres with lesser numbers of prasinophytes (with the exception of a significant peak in prasinophytes at 116.46-47 mbsf) and dinocysts. The disappearance of the acanthomorphs, if produced by sea-ice dinoflagellates, may indicate the absence of significant floating sea-ice communities and seasonal sea-ice.

The lowest 6 m of the core represent an interglacial and one of the mildest climatic intervals in the core, albeit still a cold polar setting. Lithologic studies indicate that fine-grained sediments settled on the shelf with little ice rafting indicated. Terrestrial glaciers were much reduced or completely gone from the immediate area.

Conditions were milder during the early Miocene than during most of the Quaternary (except perhaps for lithologic Unit 3.1). Overall, there was a general trend of climate deterioration upsection. The sedimentologic studies support the palynomorph interpretations, particularly those based on acanthomorphs. The sediment record suggests that the acanthomorphs were produced by organisms related to sea-ice cover; those organisms may have been sea-ice dinoflagellates.

CONCLUSIONS

This study has demonstrated that:

- 1) The CRP-1 core has yielded the first Miocene and Quaternary dinocyst assemblages from East Antarctica and the first from firmly-dated deposits of these ages from anywhere in Antarctica.

- 2) These assemblages indicate that cyst-producing dinoflagellates were present in Antarctic waters during Miocene and Quaternary times, and that deposits of those ages are worth investigating for dinocysts.
- 3) Post-Oligocene marine palynomorph assemblages of Antarctica are similar to those recovered from the Arctic. Protoperidinioid dinocysts, leiospheres, acanthomorphs and prasinophyte phycoma characterize marine palynomorph assemblages in both areas.
- 4) Modern autotrophic dinoflagellates present in the sea-ice communities of Antarctica produce organic-walled cysts morphologically similar to the acanthomorph acritarchs recovered from CRP-1 Miocene section. This suggests that some acanthomorphs from the CRP-1 core may be dinocysts.
- 5) Marine palynomorph assemblages are more diverse and abundant in Miocene than Quaternary deposits, indicating the presence of floating ice, seasonal sea-ice break up, and intervals of open water (interglacials) during part of the early Miocene.
- 6) Quaternary conditions were much harsher than those during most of the Miocene. Annual sea-ice and open water were less prevalent. Extensive ice cover and grounded glacial ice in the area prevented the development of rich palynomorph-producing plankton communities. The exception to this is the carbonate-rich Unit 3.1. This was probably deposited during interglacial times when glaciers were much reduced and icebergs scarce.
- 7) Focused microwave digestion has made possible palynologic processing for the first time in Antarctica. Rapid, safe and environmentally friendly palynologic processing can now be conducted in environmentally sensitive and remote areas. Such technology is applicable to offshore drilling platforms and shipboard work.
- 8) Thin, fine-grained pyrite coatings on palynomorphs can lead to erroneous thermal maturation interpretations.
- 9) Dinocyst diversity trends in Antarctica through Mesozoic and Cainozoic time are similar to world-wide trends. This suggests that the Antarctic record, though biased and of only modest size, is a reasonable reflection of local dinocyst diversity.

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Appendix 1 - Species list of modern motile dinoflagellate and dinocyst species mentioned in the text. Motile dinoflagellate names follow Balech (1975).

- Amphidinium hadai* Balech 1975
Batiacasphaera cooperi Hannah et al., this volume
Bitectatodinium tepikiense Wilson 1973
Brigantedinium pynei Hannah et al., this volume
Ceratium pentagonum subsp. grande Mangin 1926
Ceratium lineatum Ehrenberg (1854) Cleve 1899
Dalella chathamensis McMinn & Sun 1994
Deflandrea antarctica Wilson 1967a
Dinophysis antarctica Balech 1958
Dinophysis cornuta (Peters 1928) Balech 1967
Dinophysis contracta (Kofoid & Skogsberg 1928) Balech 1975
Dinophysis meteori Böhm 1933
Dinophysis punctata ? Jörgensen 1923
Dinophysis tenuivelata Balech 1973
Dinophysis tuberculata Mangin 1926
Diplopeltopsis granulosa Balech 1958
Diplopeltopsis minor (Paulsen 1907) Pavillard 1913
Diplopeltopsis perlata Balech 1971
Gymnodinium baccatum Balech 1965
Gymnodinium flavum Kofoid & Swezy 1921
Gymnodinium frigidum Balech 1965
Gymnodinium guttula Balech 1975
Gymnodinium minor Lebour 1917
Gymnodinium modestum Balech 1975
Gymnodinium soyai Hada 1970
Gyrodinium glaciale Hada 1970
Gyrodinium lachryma (Meunier 1910) Kofoid & Swezy 1921
Gyrodinium rhabdomante Balech 1973
Heteroschisma subantarctica Balech 1971
Impagidinium ?pallidum Bujak 1984
Impagidinium aculeatum (Wall 1967) Lentin & Williams 1981
Impagidinium sphaericum (Wall 1967) Lentin & Williams 1981
Lanternosphaeridium lanosum Morgenroth 1966a
Lejeunecysta cowiei Hannah et al., this volume
Lejeunecysta fallax (Morgenroth 1966b) Artzner & Dörhöfer 1978
Nematosphaeropsis labyrinthus (Ostenfeld 1903) Reid 1974
Oxytoxum criophilum Balech 1965
Phelodinium cramwelliae Hannah et al., this volume
Podolampus antarctica Balech 1965
Prorocentrum antarcticum (Hada 1970) Balech 1975
Protoperidinium antarcticum (Schimper in Karsten 1905) Balech 1974
Protoperidinium adeliense (Balech 1958) Balech 1974
Protoperidinium affine (Balech 1958) Balech 1974
Protoperidinium applanatum (Mangin 1926) Balech 1974
Protoperidinium archiovatum (Balech 1958) Balech 1974
Protoperidinium areolatum (Peters 1928) Balech 1974
Protoperidinium bellulum (Balech 1971) Balech 1974
Protoperidinium bipatens Balech 1973
Protoperidinium cf. crassipes Kofoid
Protoperidinium charcoti (Balech 1958) Balech 1974
Protoperidinium concavum (Mangin 1926) Balech 1974
Protoperidinium cruciferum (Balech 1971) Balech 1974
Protoperidinium curtum (Balech 1958) Balech 1973
Protoperidinium defectum (Balech 1965) Balech 1974
Protoperidinium elegantissimum (Balech 1958) Balech 1974
Protoperidinium glytopterum Balech 1973
Protoperidinium incertum (Balech 1958) Balech 1973
Protoperidinium incognitum (Balech 1959) Balech 1974
Protoperidinium latistriatum (Balech 1958) Balech 1974
Protoperidinium macrapicatum (Balech 1971) Balech 1973
Protoperidinium mangini (Balech 1971) Balech 1974
Protoperidinium mediocre (Balech 1958) Balech 1974
Protoperidinium melo (Balech 1971) Balech 1974
Protoperidinium metanatum (Balech 1965) Balech 1974
Protoperidinium nanum (Balech 1962) Balech 1974
Protoperidinium parvum (Balech 1971) Balech 1974
Protoperidinium parvicollum (Balech 1958) Balech 1973
Protoperidinium penitum (Balech 1971) Balech 1974
Protoperidinium pseudoantarcticum (Balech 1958a) Balech 1974
Protoperidinium radius (Balech 1971) Balech 1975
Protoperidinium raphanum (Balech 1958) Balech 1974
Protoperidinium rosaceum (Balech 1958) Balech 1974
Protoperidinium saltans (Meunier 1910) Balech 1973
Protoperidinium thulesense (Balech 1958) Balech 1973
Protoperidinium turbinatum (Mangin 1926) Balech 1974
Protoperidinium unipes (Balech 1962) Balech 1974
Protoperidinium variegatum (Peters 1928) Balech 1974
Pyxidinosopsis reticulata (McMinn & Sun 1994) Marret & de Vernal 1997
Selenomphix antarcticum Marret & de Vernal 1997
Vozzhemikovia apertura (Wilson 1967a) Lentin & Williams 1976

All dinocyst* names follow nomenclature listed in Lentin & Williams (1993), Marret & de Vernal (1997) or Hannah et al. (this volume).