

Terrestrial Palynology of Cape Roberts Project Drillhole CRP-3, Victoria Land Basin, Antarctica

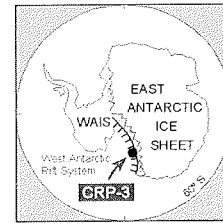
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Abstract - Sparse low diversity early Oligocene spore-pollen assemblages above *c.* 410 mbsf (metres below sea floor) in CRP-3 are dominated by *Nothofagus* pollen, and are very similar in composition to those from the lower part of CRP-2A. Anther-derived pollen aggregates, and a *Nothofagus* leaf at 44.12 mbsf show that the palynomorphs were derived from vegetation growing at the time of deposition. This woody vegetation included several species of *Nothofagus* and podocarpaceous conifers, a few other angiosperm families, and few cryptogams except for bryophytes. In favourable sites the vegetation may have comprised a low scrub or closed forest intermediate in stature and floristic richness between that of the Eocene and the limited vegetation of the late Oligocene to early Miocene. It may have been similar to *Nothofagus* woodland of the present-day Magellanic region, with summer mean daily temperatures at sea level of *c.* 10-12°C. More stunted vegetation would have existed in exposed and upland sites. Wetland vegetation appears to have been minor, although *Coptospora* may in part represent a mire community. Below *c.* 410 mbsf samples are mostly barren, probably due to non-deposition of fine particles and dilution by high sediment deposition. A meagre but relatively high diversity assemblage at 781.36 mbsf contains *Casuarina*-type pollen, unknown in the higher CRP sequence but present in Eocene strata of CIROS-1 and glacial erratics of the McMurdo Sound region. This limited data is consistent with Eocene dating of basal CRP-3 Cenozoic sediments from magnetostratigraphy.



INTRODUCTION

Cape Roberts Project drillhole CRP-3, sited 11.76 km offshore from Cape Roberts at 77.0106° S and 163.6404° E (see location map), was drilled from annual sea-ice in the Ross Sea during the period 9 October to 19 November 1999. This third and final drillhole of the Cape Roberts Project completed a programme to obtain continuous core from Cenozoic and possible older strata on the western margin of the Victoria Land Basin, in order to investigate the early history of the Antarctic ice sheet and Antarctic climate, and to elucidate the history of rifting of the Antarctic continent as recorded by uplift of the Transantarctic Mountains and formation of the basin (Cape Roberts Science Team [CRST], 2000).

Cape Roberts drillholes CRP-1 and CRP-2/2A provide a sedimentary record that spans the Early Oligocene to Early Miocene, and terrestrial palynomorphs recovered from these cores have enabled reconstruction of at least part of the contemporaneous vegetation (CRST 1998b, 1999; Raine, 1998; Askin & Raine, 2000). A preliminary survey of terrestrial and marine palynological results from CRP-3 was provided in the Initial Report for this drillhole (CRST, 2000). In this paper we discuss

Cenozoic spores and pollen (collectively termed miospores), including results from study of additional samples, and illustrate ecologically or stratigraphically-important taxa. We have not at this stage attempted an integrated account of the taxonomy and palaeoenvironmental significance of the complete Cape Roberts Cenozoic miospore sequence. The reader is referred to the Initial Report for a fuller account of redeposited palynomorphs derived from Permian to Triassic strata of the Beacon Supergroup and Jurassic sedimentary strata interbedded in volcanics of the Ferrar Group, which are also present throughout the CRP-3 Cenozoic section. Cenozoic marine palynomorphs from CRP-3 are also discussed in the Initial Report (CRST, 2000, p. 147-158) and in a paper by Hannah, Wrenn & Wilson (this volume).

STRATIGRAPHY

A summary stratigraphic column for CRP-3 is included in figures 1 and 2. Water depth at the CRP-3 drillsite is 295 m, and core was obtained from *c.* 2.8 metres below sea floor (mbsf) down to the total depth at 939.42 mbsf, with overall core recovery of 97%. The site was selected to overlap the lower Oligocene strata cored in nearby CRP-2/2A, but consensus of

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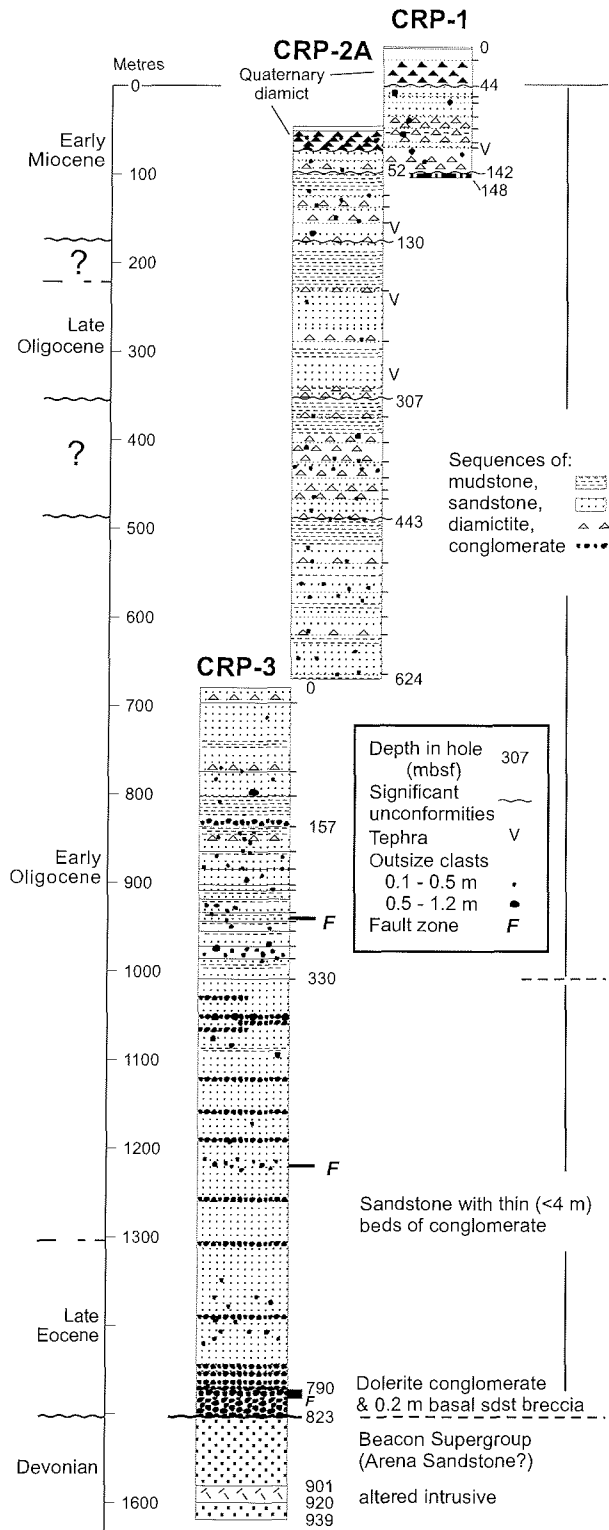


Fig. 1 - Composite log from drillholes CRP-1, 2A and 3. Data are from Cape Roberts Science Team (1998c, 1999 & 2000), with stratigraphic ages adopted for this report.

magnetostratigraphic, biostratigraphic, lithologic, and seismic data suggests there is a gap of a few tens of metres between the two sections (CRST, 2000: 187-189). Cenozoic strata were cored down to 823.11 mbsf, and igneous-intruded Devonian sandstones of the Beacon Supergroup from there to

the base of the hole. The Devonian rocks have so far proved unfossiliferous, and dating is based on petrographic comparison with similar rocks cropping out in the Transantarctic Mountains. Basal post-Beacon strata comprise a thin sandstone breccia and conglomerate interpreted as a subaerial talus or alluvial fan deposit (lithostratigraphical unit [LSU] 15.3), followed by dolerite conglomerate and minor sandstone up to c. 790 mbsf (LSU 15.2 to lower LSU 13.2), considered to have been deposited by a high-gradient fluvial system. Above this level, sandstone and conglomerate sedimentation continued in a marine setting, possibly deltaic and probably rapidly deposited below c. 330 mbsf (LSU 13.2 to 9.1). Above 330 mbsf strata also include mudstone, and diamictite of more unequivocally glaciomarine origin, deposited in an inner shelf setting. This facies is similar to that seen in the lower part of CRP-2/2A.

The distribution of fossils in the Cenozoic section follows that of the mud component of the sediments, and strata are for the most part poorly fossiliferous below the upper c. 200 m of the core. In the upper c. 200 m, dating is based on siliceous microfossils and calcareous nannofossils combined with magnetostratigraphy, and indicates that the top of the section lies in the mid-part of magnetochron C12r, *i.e.* in the Early Oligocene, in accord with dating of the lowermost part of the CRP-2/2A section. Below this level these fossils are absent, and although foraminifera, marine macrofossils, and marine and terrestrial palynomorphs occur consistently down to c. 330 mbsf, and sporadically to near the base of the Cenozoic section, the biostratigraphic utility of these groups is low and dating is based on a count-back of magnetochrons. On this basis, and taking into account likely sedimentation rates, a zone of predominantly reversed magnetic polarity in the lower part of the section, up to c. 630 mbsf, is at least as old as magnetochron C13r and therefore Late Eocene or older (Florindo et al., this volume) although dinoflagellate workers prefer an age no older than uppermost Eocene (Hannah & Fielding et al., this volume).

PALYNOLOGICAL PROCESSING

Palyнологical sample preparation followed the techniques described by the Cape Roberts Science Team (1998a) and in more detail by Simes & Wrenn (1998). All preparation was performed at the McMurdo Station laboratory during the 1999 drilling season, samples being assigned "P" prefix laboratory numbers in sequence with those of previous CRP drillholes. Between 5 and 15 g of rock were processed for each sample. Sample digestion in hydrochloric and hydrofluoric acid using a ProLabo M401 microwave apparatus was followed by seven minutes oxidation with concentrated nitric acid, and decanting using a swirling method. Most samples were sieved through a 212 µm mesh sieve to remove

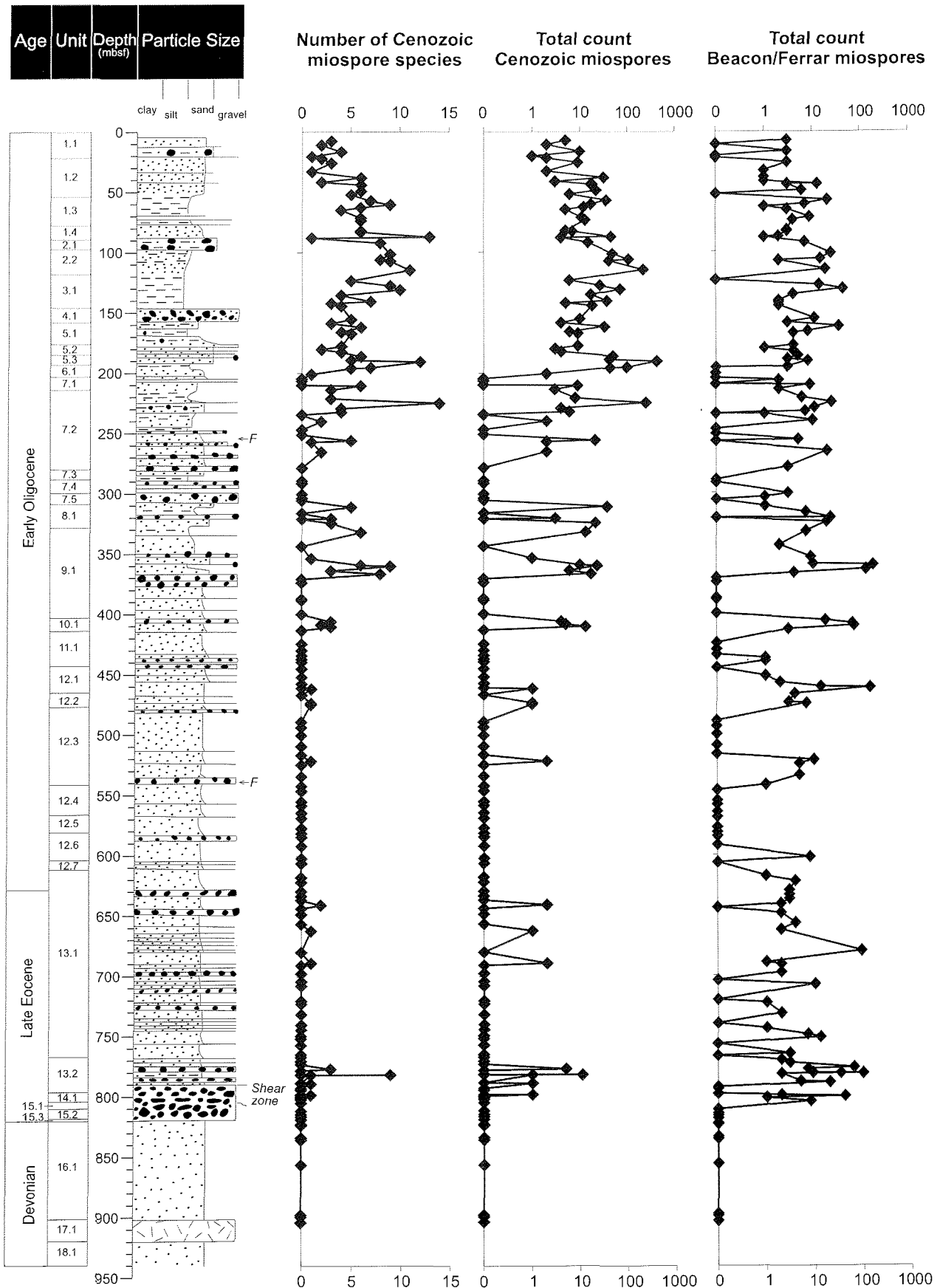


Fig. 2 - Summary diagram showing the distribution of terrestrial palynomorphs in CRP-3. Species diversity of Cenozoic miospores is expressed as numbers of taxa identified in samples. Total abundance of Cenozoic and of redeposited Beacon Supergroup and Ferrar Group miospores (Permian to Jurassic) is based on counts of all specimens encountered in samples (which were of approximately equal size and completely examined). Columns on the left include age (see text), lithostratigraphic units (e.g. 1.1), and lithologic column as described in CRST (2000), F = fault.

coarse mineral grains and other debris. Those containing significant detrital coal fragments were passed through a 125 µm sieve. Sieved residues were further cleaned of unwanted mineral matter by heavy liquid separation with sodium polytungstate (2.3 specific gravity). The final step for most organic residues was sieving on a 6 µm mesh cloth using a Vidal Filter apparatus (Raine & Tremain, 1992) to remove fine particles. Strew-mount microscope slides were made with glycerin jelly medium. Palynological slides for the Cape Roberts Project drillholes are deposited with the National Palaeontological Collection at Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand.

RESULTS

Palynology in the Initial Report was based upon examination of a total of 120 samples, including all "fast-track" samples and additional samples to secure a sample spacing of *c.* 10 m or less through the Cenozoic section. Results from a further 64 samples have been incorporated in this paper (Tab. 1), including all palynological samples collected from below *c.* 350 mbsf. A further 24 samples prepared from the upper part of the core remain to be studied, however the new work has so far confirmed palynofloral trends previously reported.

RECYCLED AND CONTAMINANT PALYNOMORPHS

Within the Cenozoic section, both presumed contemporaneous and recycled components can be recognised on the basis of preservation state and known stratigraphical range. The recycled component includes a few Cenozoic forms but mainly comprises Permian to Mesozoic miospores. Preservation of the Cenozoic palynomorphs, including presumed contemporaneous and recycled specimens, is generally good to very good. There are some poorly preserved specimens, however, that are broken and torn, or have scarring from authigenic pyrite crystal growth. The Cenozoic specimens are mostly light yellow to yellow in colour, although some have a darker (yellow-orange) hue. Recycled Permian and lower Mesozoic spores and pollen occur throughout much of CRP-3. These miospores, which originate from the Beacon Supergroup and sedimentary interbeds of the Ferrar Group volcanics, can be distinguished by their distinctive morphology, and usually darker exinal colour (yellow-orange through brown to black) relative to the light yellow contemporaneous miospores.

The extent of reworking of Cenozoic (or possible Late Cretaceous) spores and pollen from older rocks appears to be less than in the upper part of CRP-2/2A. Noticeably deeper yellow specimens with adherent organic matter, identified as *Peninsulapollis*

cf. gillii (177.76 mbsf, Fig. 4s) and *Tricolporites cf. paenestriatus* (83.02 mbsf, Figs. 4t, 4u) are confidently considered to be redeposited. Both species were reported from the lower section of CIROS-1 by Mildenhall (1989). Rare specimens of *P. gillii*, considered to possibly be redeposited, were observed in the McMurdo Sound Eocene erratics by Askin (2000). In Australasia, *P. gillii* has a range of Late Cretaceous to Eocene (Dettmann & Jarzen, 1988), and *T. paenestriatus* of Eocene to Pliocene (Stover & Partridge, 1973; Macphail 1999). Rare occurrences of the gymnosperms, *Dilwynites granulatus*, *Microcachrydites antarcticus*, and *Trichotomosulcites subgranulatus*, which occur in samples that lack abundant and presumed contemporaneous *Nothofagidites*, are similar to sporadic occurrences in CRP-1 and CRP-2/2A, and are also likely to be recycled specimens. Some of the fern spore specimens may also be recycled, as these occur in only a few samples.

Specimens of Asteraceae (Tubuliflorae) pollen were encountered at 781.36 and 797.88 mbsf. These lack protoplasm, and may be fossil. Mildenhall (1989) recorded several similar specimens in the lower part of the CIROS-1 sequence, tentatively regarding these as contamination. Pollen of the Asteraceae (= Compositae) family, which are common weeds and thus potential laboratory contaminants, first appears in Australasian sequences in the late Oligocene (Pocknall & Mildenhall, 1984), but possibly earlier at DSDP Site 254 in the Indian Ocean (Kemp & Harris, 1977). Recovery of further specimens is required to confirm the fossil nature of the CRP-3 and CIROS-1 specimens.

MIOSPORE ABUNDANCE

Specimen counts presented in tables 1a and 1b result from study of the entire organic residue from palynological processing. Since the weight of sample processed was fairly uniform, usually 10 g in the section above *c.* 380 mbsf, and 10 to 20 g below that level, total counts are a reasonable guide to sample-to-sample variation in miospore abundance (Fig. 2). This varied from moderate (>100 specimens/10 g), through low (10 to 100 specimens/10 g), to sparse (<10 specimens/10 g) or nil. We also examined 6 samples from the Beacon Supergroup section below 823.11 mbsf. Consistent with the coarse grain size and oxidising palaeoenvironment represented, these proved to be barren of palynomorphs or other organic material.

The Cenozoic section can be divided into three intervals on the basis of Cenozoic miospore abundance. The lowest interval, from the base up to *c.* 410 mbsf, is characterised by long barren intervals and sporadic sparse occurrences. From *c.* 410 mbsf up to *c.* 200 mbsf short intervals of sparse to low abundance alternate with barren intervals of similar thickness. Above *c.* 200 mbsf, Cenozoic miospores

occur in all samples, with abundance reaching moderate levels in a few samples. Highest abundances occur in mudstones and sandy mudstones at 106.22 mbsf (count of 108, LSU 2.2), 114.90 mbsf (count 224, LSU 2.2), 131.17 mbsf (count 72, LSU 3.1), 190.77 mbsf (count 416, LSU 6.1), and 225.11 mbsf (count 250, LSU 7.2). These abundances exceed those seen in CRP-1 and CRP-2/2A, the most similar being a count of 64 miospores in mudstone at 575.36 mbsf in the lower part of CRP-2A.

Peaks in recycled Beacon/Ferrar miospore occurrences correspond in a general way with many of the peaks in occurrences of contemporaneous specimens, and correspond to finer sediment grain size. Below 410 mbsf, where contemporaneous palynomorphs are sparse or absent, peaks in abundance may also be due to recycled clasts of palynologically-rich sediment. The general rarity of Cenozoic miospores in the lower part of the CRP-3 core is believed to result from, in part, removal of the fine fraction of the sediment by winnowing and, in part, dilution by rapid influx of sediment. Sparseness of vegetation in the surrounding landscape could also have contributed to the low abundance of miospores.

COMPOSITION OF ASSEMBLAGES

Diversity varies in concert with total abundance of miospores (Fig. 2), being higher in the samples with greater abundance, but in general is low. Relatively high total counts in the upper c. 410 m of the core are mostly due to high levels of *Nothofagidites* spp., particularly of *N. lachlaniae* and undifferentiated *fusca* group species. Other relatively abundant taxa include *N. flemingii*, *N. cf. flemingii*, and various species of *Podocarpidites*. Aggregates of *Nothofagidites lachlaniae* and *Nothofagidites fusca* group pollen grains (e.g. Fig. 4h) occur at 101.59, 114.90, 131.17 and 225.11 mbsf, in association with high counts of individual specimens. Mildenhall (1989) observed similar aggregates of *Nothofagidites* pollen in CIROS-1. As suggested by Mildenhall, such aggregates are very likely to be due to incorporation of anthers in the sediment. Their fragility suggests that they are not recycled but transported, with very little disruption, from contemporaneous vegetation. This is supported by the presence of a leaf of *Nothofagus* found in the CRP-3 core at 44.12 mbsf (Cantrill, this volume).

In the upper c. 410 m of core, the taxonomic composition of the flora is very similar to that encountered in the lower part of CRP-2A, with a similar number of species and few different species being encountered. Although some of the same species occur sporadically in the lower part of the CRP-3 section, the dominance of *Nothofagidites* and *Podocarpidites* species is less evident. Despite a low total Cenozoic miospore count of only 11 specimens, the sample at 781.36 mbsf has a relatively high taxonomic diversity with 9 species present.

Bryophytic spores of *Coptospora* spp. occur consistently through the sequence (Figs. 3a, 3b); most of these are probably referable to *Coptospora* sp. c of Raine (1998), and the *Coptospora* sp. from CIROS-1 illustrated by Mildenhall (1989, Pl. 2, Fig. 14). The only other certain bryophytic spore encountered was a single broken specimen of *Ricciaesporites* sp. similar to that seen in CRP-2A, which occurs at 781.36 mbsf. Lycopod spores are noted for the first time in the sequence of CRP wells, as *Lycopodiumsporites* sp., and occur consistently through the upper part of CRP-3. These differ from the exotic *Lycopodium* spores (used as a tracer in preparations) in having a finer-meshed reticulate sculpture and elevated membranous labra adjacent to the laesurae. Ferns are represented by rare occurrences of *Cyathidites minor*, *Laevigatosporites* spp. (Fig. 3c), and *Rugulatisporites* sp. It is possible that some of these fern spores are recycled from Eocene or older strata.

Gymnosperms are mainly represented by *Podocarpidites* species. *Podocarpidites* sp. a, which had a reported LAD at 316.50 mbsf in CRP-2A (CRST, 1999, p. 136), occurs in a few samples. *Podocarpidites* sp. b and *P. cf. exiguus* (Fig. 3d) also occur in both CRP-2/2A and CRP-3. *Podocarpidites* sp. d (Figs. 3e, 3f) is an uncommon form with distinctive rugulate cappa. *Podocarpidites* sp. e, a small form with clearly reticulate saccus mesexine (Figs. 3g, 3h), appears to have a peak in abundance between c. 71 and 131 mbsf. *Dilwynites granulatus*, *Trichotomosulcites subgranulatus* and *Microcachryidites antarcticus* (Fig. 3i) are, as in CRP-2/2A comparatively rare and may be recycled from older strata. A distinctive form, *cf. Trichotomosulcites* sp. (Figs. 3j, 3k), is not well-understood morphologically and may be an undescribed species.

The diversity of *Podocarpidites* species is possibly greater than is immediately apparent from table 1. Taxonomic differentiation within the genus is difficult, and many folded specimens have been recorded simply as "*Podocarpidites* spp." A similar situation applies with *Nothofagidites*. *Nothofagidites asperus* (Fig. 4g) is a distinctive large species which represents the *menziesii* pollen-morphological group. Occasional specimens were also recorded in CRP-1 and CRP-2/2A. With the exception of *N. asperus*, all specimens belong to the *fusca* pollen-morphological group. *N. flemingii* (Fig. 4f) is readily recognisable on the basis of its relatively large size, minimal sculpture, and pronounced apertural thickenings (*costae*). Atypically smaller specimens have been recorded as *N. cf. flemingii*. The distinction between more coarsely sculptured species of the *fusca* group present in the Cape Roberts cores requires further investigation. Specimens differing from typical *N. lachlaniae* (e.g. larger and with larger spines, Fig. 4e) have been recorded simply as *Nothofagidites* spp. (*fusca* group).

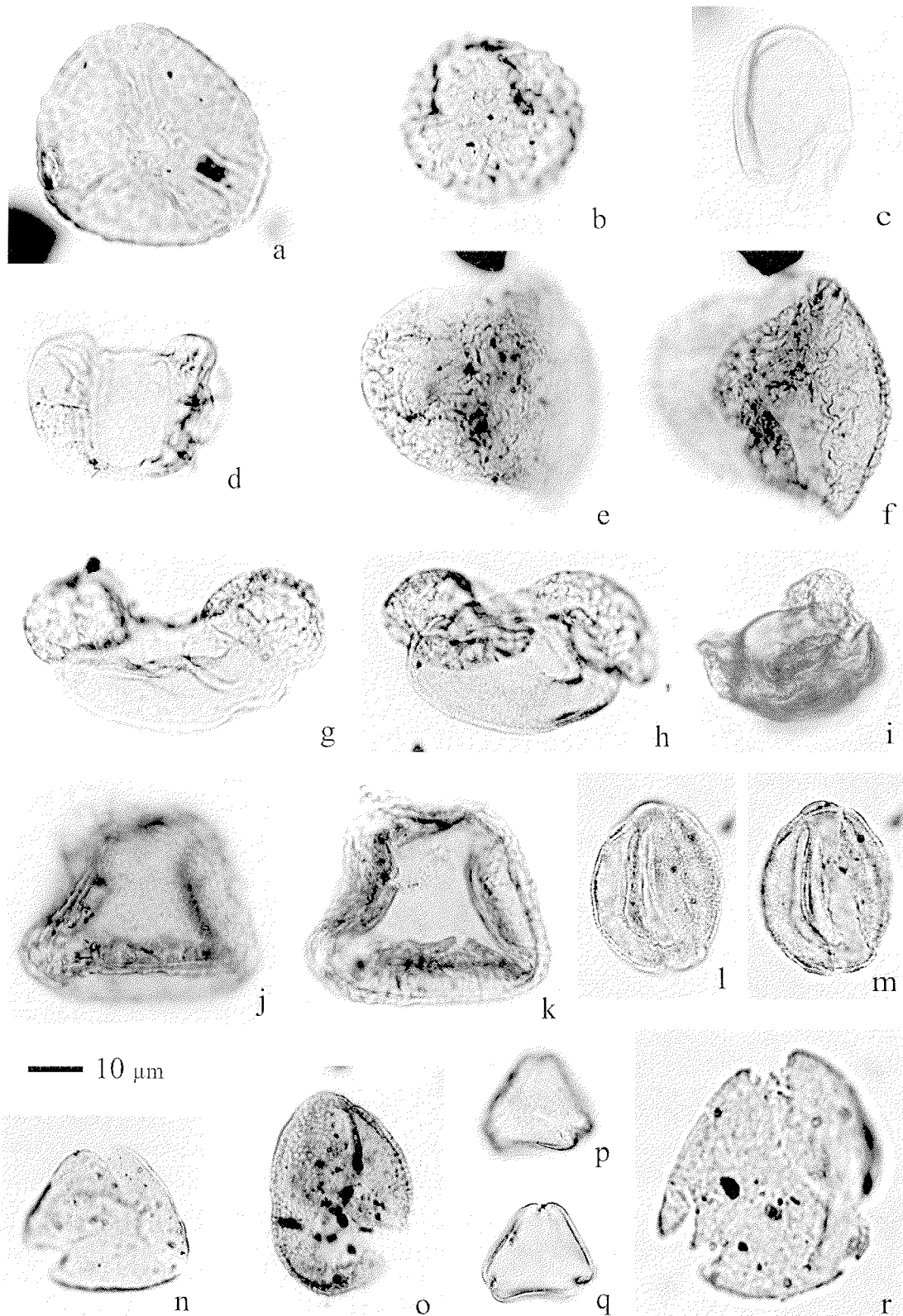


Fig. 3 - Photomicrographs of selected Cenozoic spores and pollen from CRP-3, at uniform magnification (scale bar = 10 μ m). a) *Coptospora* sp.(= *Coptospora* sp.c of Raine, 1998), depth 87.47-87.49 mbsf, slide P232/3, England Finder coordinates T50(4), maximum dimension 45 μ m; b) *Coptospora* sp., 131.17-131.19 mbsf, P220/3, U38(3), 35 μ m; c) *Laevigatosporites ovatus* Wilson & Webster, 114.90-114.92 mbsf, P216/2, X40(2), 35 μ m; d) *Podocarpidites* cf. *exiguus* Harris, 114.90-114.92 mbsf, P216/1, T50(4), breadth of corpus 25 μ m; e, f) *Podocarpidites* sp.d, two focal levels, 107.38-107.40 mbsf, P183/3B, G35(0), breadth of corpus 48 μ m; g) *Podocarpidites* sp.e, 131.17-131.19 mbsf, P220/1, S46(3), length 55 μ m; h) *Podocarpidites* sp.e, 114.90-114.92 mbsf, P216/4, G55(1), length 51 μ m; i) *Microcachryidites antarcticus* Cookson, 92.28-92.30 mbsf, P233/2, K50(4), 35 μ m; j, k) cf. *Trichotomosulcites* sp., two focal levels, 359.16-359.18 mbsf, P257/1, K53(4), 46 μ m; l, m) *Tricolpites* sp. (cf. *Tricolpites* sp.a of Raine, 1998), two focal levels, 256.06-256.09 mbsf, P253/1, B42(0), 33 μ m; n) *Tricolpites* sp.b of Askin & Raine (1998), 320.70-320.72 mbsf, P273/1, O43(2-4), 31 μ m; o) *Tricolpites* sp.d, 107.38-107.40 mbsf, P183/2B, N22(1), 39 μ m; p, q) *Tricolpites* sp.f, two focal levels, 776.64-776.66 mbsf, P364/2, D44(2), 21 μ m; r) ?*Myrtaceidites* sp., 210.71-210.73 mbsf, P243/2, H44(1), 38 μ m.

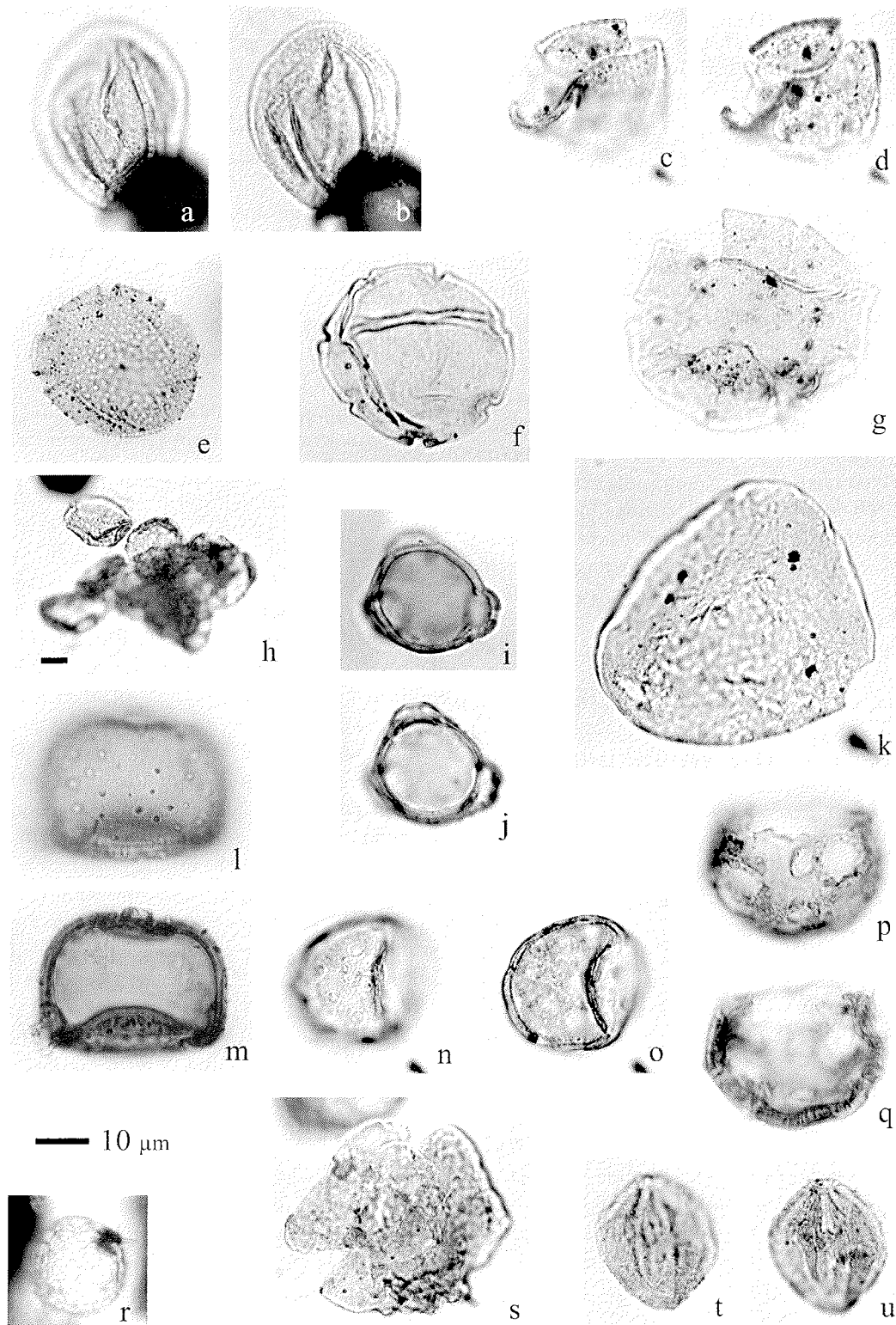


Fig. 4 - Photomicrographs of selected pollen from CRP-3, at uniform magnification (scale bar = 10 μm) except for figure *h*. Figures *a-r* are thought to be Cenozoic taxa penecontemporaneous with deposition, while specimens illustrated in figures *s-u* are redeposited from older Cenozoic or possibly Late Cretaceous strata. *a, b*) Ranunculaceae, two focal levels, depth 60.54-60.56 mbsf, slide P225/1, England Finder coordinates M39(0), maximum dimension 37 μm ; *c, d*) ?Stylidiaceae, two focal levels, 195.62-195.64 mbsf, P239/2, M38(4), 30 μm ; *e*) *Nothofagidites* sp. (*fusca* group), 114.90-114.92 mbsf, P216/1, N45(0), 32 μm ; *f*) *Nothofagidites flemingii* (Couper) Potonié, 114.90-114.92 mbsf, P216/1, S34(0), 37 μm ; *g*) *Nothofagidites asperus* (Cookson) Romero, 82.36-82.38 mbsf, P186/2, X35(2), 46 μm ; *h*) aggregate of pollen of *Nothofagidites lachlaniae* (Couper) Pocknall & Mildenhall (scale bar = 10 μm), 101.59-101.61 mbsf, P213/3, B45(0), individual pollen grains *c.* 27 μm diameter; *i, j*) *Myricipites harrisii* (Couper) Dutta & Sah, 781.36-781.38 mbsf, P342/11, L47(2), 27 μm ; *k*) *Triporopollenites* sp., 140.67-140.69 mbsf, P222/3, V34(1), 53 μm ; *l, m*) ?Campanulaceae, 87.47-87.49 mbsf, P232/3, A48(0), 36 μm ; *n, o*) Caryophyllaceae, two focal levels, 127.88-127.90 mbsf, P219/3, K34(0), 27 μm ; *p, q*) Caryophyllaceae (*Stellaria* type), two focal levels, 781.36-781.38 mbsf, P342/7, S46(2), 35 μm ; *r*) *Chenopodiipollis* sp., 265.41-265.43 mbsf, P256/1, K50(0), 19 μm ; *s*) *Peninsulapollis cf. gillii* (Cookson) Dettmann & Jarzen, 177.76-177.78 mbsf, P234/3, F38(3), 43 μm ; *t, u*) *Tricolporites cf. paenestriatus* Stover, 83.02-83.04 mbsf, P209/1, L33(2), 26 μm .

tetracolpate pollen with microechinate sculpture recovered from 195.62 mbsf (Figs. 4c, 4d) may be referable to Stylidiaceae (there is also resemblance to Ranunculaceae). Possible Stylidiaceae pollen was recorded from the lower Miocene section of CRP-2/2A (Askin & Raine 2000, Fig. 2i). The present specimen appears to differ, for example in possessing larger echinae.

Four triporate pollen taxa are recorded. *Myricipites harrisii* (Figs. 4i, 4j) is present only in the lower part of the CRP-3 section at 781.36 mbsf. A doubtful specimen also occurs at 474.73 mbsf. It has not previously been recorded in the Cape Roberts cores. *Proteacidites* sp. (not illustrated) is a small form with granulate exine. *Triporopollenites* sp. (Fig. 4k) is a large psilate form possibly conspecific with a specimen illustrated by Raine (1998, Fig. 2d). A distinctive type recorded as ?Campanulaceae occurs at 87.47 mbsf (Figs. 4l, 4m). This species has scattered spines, thickened pore annuli, and protruding pore membranes, and may be conspecific with the species from CIROS-1 recorded as ?*Proteacidites spiniferus* by Mildenhall (1989, Pl. 2, Figs. 8-9).

Three periporate pollen species, all possibly referable to Caryophyllaceae, are recorded as Caryophyllaceae *Stellaria* type (only at 781.36 mbsf, Figs. 4p, 4q), ?Caryophyllaceae (Figs 4n, 4o), and *Chenopodipollis* sp. (Fig. 4r). The latter two are similar to species occurring in CRP-1 (CRST, 1998b; Raine, 1998, Figs. 2m & 2k-l respectively).

DISCUSSION

BIOSTRATIGRAPHY

Marchantiaceae and *Tricolpites* sp. a, two characteristic taxa of the uppermost Oligocene to lower Miocene section of CRP-2/2A and the lower Miocene section of CRP-1, are not recorded in CRP-3. As noted above, the composition and relative abundances of taxa in the upper part of the CRP-3 sequence, down to c. 410 mbsf, resemble those of the lowermost Oligocene part of the CRP-2A section. Other than noting this consistency, the lack of established datums at present precludes closer correlation. The apparent absence of the acme of *Podocarpidites* sp. e in CRP-2, however, may suggest that the sequence between c. 71 and 131 mbsf in CRP-3 has no equivalent in CRP-2, in accord with other lines of evidence (CRST, 2000, p.187).

The diversity of Cenozoic taxa present in the upper part of the CRP-3 sequence is slightly less than that reported from CIROS-1 by Mildenhall (1989), and less than in many of the middle to late Eocene "McMurdo Sound erratics" (McIntyre & Wilson, 1966; Askin, 2000). A notable absence from CRP-3 is pollen of the *brassii* group of *Nothofagidites*, present in the lower section of CIROS-1, and in the

McMurdo erratics. If the CIROS-1 occurrences can be regarded as contemporaneous with deposition, absence of the *N. brassii* group from CRP-3 points to a younger age for the CRP-3 sequence above c. 410 mbsf. Again, this is consistent with results from marine biostratigraphy and magnetostratigraphy in CRP-3 (CRST, 2000; Hannah & Fielding et al., this volume) and the latest interpretations of the age of the fossiliferous CIROS-1 strata (Hannah et al., 1997; Wilson et al., 1998).

Below c. 410 mbsf in CRP-3 (this depth may correspond to the upper part of magnetochron C13n, i.e. about 33.2 Ma and very early Oligocene, according to Florindo et al., this volume), paucity of the assemblages and uncertainty about recycling and contamination prevent any conclusion being drawn with confidence. We note, however, that although rich "warm-climate" preglacial Eocene assemblages were not encountered in CRP-3, there is some evidence in support of such a correlation. Firstly, although only a small number of miospores was recovered, species diversity is apparently high in the 781.36 mbsf sample. This may suggest more diverse parent vegetation, and therefore that a warmer climate prevailed. Second, the records of *Myricipites harrisii* at 781.36 and possibly 474.73 mbsf are the first record for the CRP sequence of wells. This taxon, which represents pollen of the angiosperm family Casuarinaceae, is characteristic and abundant in the Eocene of New Zealand and Australia, and also occurs in the McMurdo erratics (McIntyre & Wilson, 1966; Askin, 2000) and MSSTS-1 drill core (Truswell, 1986). In the MSSTS-1 sequence specimens are common through the upper Oligocene, lower Miocene, and Quaternary sections (Truswell, 1986, recorded as *Triorites harrisii*), and were interpreted as recycled from older sediments. Rare specimens were recorded only in the lowermost part of the CIROS-1 sequence by Mildenhall (1989, as *Haloragacidites harrisii*), in the section now dated as middle Eocene, magnetochron C16n.2n (Wilson et al., 1998). In the glacial erratics from McMurdo Sound dated as middle to upper Eocene on dinoflagellate evidence (Group 1 of Askin, 2000), *M. harrisii* (recorded as *H. harrisii*) occurs sparsely in only two samples. McIntyre & Wilson (1966) noted it as a minor component (*T. harrisii*) in three of five erratics samples studied.

In New Zealand, the main vegetational response to late Eocene climatic cooling occurred some time before the end of the Eocene (e.g. Raine, 1984; Pocknall, 1989), near the Kaiatan/Runangan Stage boundary (35.5 Ma, upper C16n: Morgans et al., 1996), and was reflected in the palynoflora by a transition from *Myricipites harrisii*-dominated palynofloras to those dominated by *Nothofagidites* of the *brassii* group. It is likely that a corresponding vegetational change occurred at a similar time, or

even earlier, in Antarctica. That such a change occurred is attested to by the absence of a large proportion of the rich Eocene flora, as noted above, in the upper CRP-3 record. Whether the specimens of *M. harrisii* in CRP-3 (and those in CIROS-1) are recycled is unclear. As noted, recycling of *M. harrisii* would be unique within the known CRP sequence. If the specimens are not recycled, then their presence may point to a Kaiatan-equivalent or older age, *i.e.* greater than 35.5 Ma, for these strata.

PALAEOENVIRONMENTAL SIGNIFICANCE

It should be noted that cyclicality in sedimentary facies (Powell et al., this volume) indicates there was significant fluctuation in glacial climate during the Oligocene and lower Miocene CRP record. The spore-pollen assemblages do not provide a truly continuous record of vegetation. The palynological record must also have been smoothed by sedimentation processes such as penecontemporaneous reworking. Further, the record emphasises the more favourable phases for plant growth, as periods unfavourable for vegetation will have provided less abundant spores and pollen to the sediments. Temperature estimates suggested here therefore apply to warmer phases during the relevant intervals.

Raine (1998) and Askin & Raine (2000) noted a close similarity of spore-pollen assemblages of the early Miocene and late Oligocene in CRP-1 and CRP-2/2A to those of the Meyer Desert Formation of the Sirius Group in the Beardmore Glacier area of the Transantarctic Mountains (Askin & Markgraf, 1986), and inferred that they resulted from a similar tundra-like parent vegetation with sparse shrub *Nothofagus* as well as a few other angiosperms, podocarps, and bryophytes. Comparison with present day climatic data for the Antarctic region (Longton, 1988) suggests that partial cover of low-diversity woody vegetation, but beyond the poleward limit of extensively developed woodland would suggest mean January daily temperatures of at least 7°C but less than about 10°C*. Polewards, vegetation beyond the limit of extensive shrubland but with important flowering plants and profuse bryophytes would imply mean January temperatures of at least 1-2°C but probably less than 7°C. Francis & Hill (1996) suggested from wood anatomy that the dwarf growth forms of *Nothofagus beardmorensis* in the Meyer Desert Formation may have grown in summer temperatures around 5°C or slightly higher. Mean summer daily temperatures of *c.* 5-7°C are accordingly proposed for the late Oligocene to early Miocene period (*c.* 25-17 Ma) at Cape Roberts.

The *Nothofagidites*-dominated palynofloras of the lowermost section of CRP-2 and upper CRP-3,

correlated with the early Oligocene, represent a more luxuriant development of woody vegetation. However, as noted above, assemblages in the upper part of CRP-3 never reach the species richness and abundance seen in the Eocene McMurdo Sound erratics (McIntyre & Wilson, 1966; Askin, 2000) or in the Eocene lower part of CIROS-1 (Mildenhall, 1989). Instead, the CRP-3 assemblages suggest low diversity woody vegetation that included several species of *Nothofagus* and podocarpaceous conifers, a few other angiosperm families, and few cryptogams except for bryophytes (mosses and liverworts). Many of the important components of the prior Eocene flora are missing, for example several species of Proteaceae, various other angiosperms, gymnosperms and cryptogams. In favourable sites the vegetation may have comprised a low scrub or closed forest intermediate in stature and floristic richness between that of the Eocene and the limited vegetation of the late Oligocene to early Miocene. More stunted vegetation would have existed in exposed and upland sites. Wetland vegetation, which would be indicated by the presence of monocotyledonous angiosperms such as Cyperaceae and *Phormium* (CRP-2; CRST, 1999; Askin & Raine, 2000), appears to have been minor, although *Coptospora* may in part represent a mire community.

Phytolith analyses (Thorn, this volume) also indicate a prominent woody component to the vegetation during the period represented by the upper *c.* 410 m of CRP-3 core. Smooth spherical phytoliths, which are common in the core, are typical of *Nothofagus* spp., and other angiosperm types including possibly Proteaceae are also present. Differing from the pollen record, Thorn suggests the presence of Palmae (= Arecaceae, palms) and Gramineae (= Poaceae, grasses). Both families produce distinctive and reasonably abundant pollen, but neither have been observed in the Cape Roberts pollen record, or in the Eocene McMurdo Sound erratics. However Mildenhall (1989: 125) suggested some records of Gramineae from CIROS-1 might represent *in situ* pollen.

Modern-day vegetation in the Magellanic Region at the southern tip of South America is put forward as a possible analogue of the Early Oligocene vegetation represented in the upper CRP-3 core. In this region at the southern limit of tree growth, low *Nothofagus* forests of very limited taxonomic diversity give way to stunted *Nothofagus* shrubland above the altitudinal treeline, only *c.* 650 m above sea level at Punta Arenas (McQueen, 1976). Climatic data for Punta Arenas (*e.g.* McQueen, 1976; Muller, 1982), which has a mean summer daily temperature of 10.8°C, suggest a range of *c.* 10-12°C for the early Oligocene (*c.* 33-31 Ma) period at Cape Roberts.

* The reader should note that temperatures quoted as July (southern winter) monthly means in Raine (1998) in fact should have been quoted as January (southern summer) monthly means.

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REFERENCES

- Askin R.A., 2000. Spores and pollen from the McMurdo Sound erratics, Antarctica. In: Stilwell J.D. & Feldmann R.M. (eds.), *Palaeobiology and Palaeoenvironments of Eocene Rocks, McMurdo Sound, East Antarctica*, Antarctic Research Series, **76**, American Geophysical Union, pp. 161-181.
- Askin R.A. & Markgraf V., 1986. Palynomorphs from the Sirius Formation, Dominion Range, Antarctica. *Antarctic Journal of the United States*, **21**, 34-35.
- Askin R.A. & Raine J.I., 2000. Oligocene and Early Miocene terrestrial palynology of Cape Roberts Drillhole CRP-2/2A, Victoria Land Basin, Antarctica. *Terra Antarctica*, **7**, 493-501.
- Cantrill D., 2001. Early Oligocene *Nothofagus* from CRP-3, Antarctica: implications for the vegetation history. This volume.
- Cape Roberts Science Team, 1998a. Background to CRP-1, Cape Roberts Project, Antarctica. *Terra Antarctica*, **5**, 1-30.
- Cape Roberts Science Team, 1998b. Miocene Strata in CRP-1, Cape Roberts Project, Antarctica. *Terra Antarctica*, **5**, 63-124.
- Cape Roberts Science Team, 1998c. Summary of results from CRP-1, Cape Roberts Project, Antarctica. *Terra Antarctica*, **5**, 125-137.
- Cape Roberts Science Team, 1999. Initial Report on CRP-2/2A. *Terra Antarctica*, **6**, 1-173.
- Cape Roberts Science Team, 2000. Studies from Cape Roberts Project. Initial Report on CRP-3. *Terra Antarctica*, **7**, 1-209.
- Dettmann M.E. & Jarzen D.M., 1988. Angiosperm pollen from uppermost Cretaceous strata of southeastern Australia and the Antarctic Peninsula. *Memoir of the Association of Australasian Palaeontologists*, **5**, 217-237.
- Florindo F., Wilson G.S., Roberts A.P., Sagnotti L. & Verosub K.L., 2001. Magnetostratigraphy of late Eocene - early Oligocene glaciomarine sediments from the CRP-3 core, Victoria Land Basin, Antarctica. This volume.
- Francis J.E. & Hill R.S., 1996. Fossil plants from the Pliocene Sirius Group, Transantarctic Mountains: evidence for climate from growth rings and fossil leaves. *Palaeos*, **11**, 389-396.
- Hannah M.J., Cita M.B., Coccioni R. & Monechi S., 1997. The Eocene/Oligocene boundary at 70° South, McMurdo Sound, Antarctica. *Terra Antarctica*, **4**, 79-97.
- Hannah M.J., Fielding C., Florindo F. & Harwood D., 2001. Chronostratigraphy of CRP-3, Victoria Land Basin, Antarctica. This volume.
- Hannah M.J., Wrenn J.H. & Wilson G.J., 2001. Early Oligocene marine palynomorphs from CRP-3, Victoria Land Basin, Antarctica. This volume.
- Kemp E.M. & Harris W.K., 1977. The palynology of early Tertiary sediments, Ninetyeast Ridge, Indian Ocean. *Special papers in palaeontology*, **19**, 70 p.
- Longton R.E., 1988. *The biology of polar bryophytes and lichens*. Cambridge University Press, Cambridge.
- Macphail M.S. 1999. Palynostratigraphy of the Murray Basin, inland southeastern Australia. *Palynology*, **23**, 197-240.
- McIntyre D.J. & Wilson G.J., 1966. Preliminary palynology of some Antarctic Tertiary erratics. *New Zealand Journal of Botany*, **4**, 315-321.
- McQueen D.R., 1976. The ecology of *Nothofagus* and associated vegetation in South America. *Tiutara*, **22**, 38-68.
- Mildenhall D.C., 1989. Terrestrial palynology. In: Barrett P.J. (ed.), *Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound*, DSIR Bulletin, **245**, 119-127.
- Morgans H.E.G., Scott G.H., Beu A.G., Graham I.J., Mumme T. C., St George W. & Strong C.P., 1996. New Zealand Cenozoic time scale (1996). *Institute of Geological and Nuclear Sciences, Science Report*, **96/38**.
- Muller M.J., 1982. *Selected climate data for a global set of standard stations for vegetation science*. W Junk, The Hague, 306 p.
- Pocknall D. T., 1989. Late Eocene to Early Miocene vegetation and climate history of New Zealand. *Journal of the Royal Society of New Zealand*, **19**, 1-18.
- Pocknall D.T. & Mildenhall D.C., 1984. Late Oligocene-early Miocene spores and pollen from Southland, New Zealand. *New Zealand Geological Survey Palaeontological Bulletin*, **51**, 66 p.
- Powell R.D., Fielding C.R., Laird M.G., Naish T.R., van der Meer J., 2001. Depositional environments for strata cored by CRP-3, Victoria Land Basin, Antarctica: palaeoglaciological and palaeoclimatic inferences. This volume.
- Raine J.I., 1984. Outline of a palynological zonation of Cretaceous to Palaeogene terrestrial sediments in West Coast Region, South Island, New Zealand. *New Zealand Geological Survey Report NZGS*, **109**, 82 p.
- Raine J.I., 1998. Terrestrial palynomorphs from Cape Roberts Project drillhole CRP-1, Ross Sea, Antarctica. *Terra Antarctica*, **5**, 539-548.
- Raine J.I. & Tremain R., 1992. Apparatus for rapid sieving of palynological residues. *New Zealand Geological Survey report PAL*, **151**, 14 p.
- Simes J. & Wrenn J.H., 1998. Palynologic Processing in Antarctica. *Terra Antarctica*, **5**, 549-552.
- Stover L.E. & Partridge A.D., 1973. Tertiary and Late Cretaceous spores and pollen from the Gippsland Basin, southeastern Australia. *Proceedings of the Royal Society of Victoria*, **85**, 237-286.
- Thorn V., 2001. Oligocene and Early Miocene Phytoliths from CRP-2/2A and CRP-3, Victoria Land Basin, Antarctica. This volume.
- Truswell E.M., 1986. Palynology. In: Barrett P.J. (ed.), *Antarctic Cenozoic history from the MSSTS-1 drillhole, McMurdo Sound*, *DSIR Bulletin*, **237**, 131-134.
- Wilson G.S., Roberts A.P., Verosub K.L., Florindo F. & Sagnotti L., 1998. Magnetobiostratigraphic chronology of the Eocene-Oligocene transition in the CIROS-1 core, Victoria Land margin, Antarctica: implications for Antarctic glacial history. *Geological Society of America bulletin*, **110**, 35-47.