

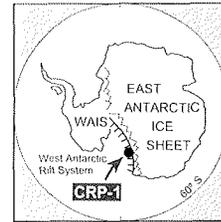
Terrestrial Palynomorphs from Cape Roberts Project Drillhole CRP-1, Ross Sea, Antarctica

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Abstract - Sparse pollen and spores from the lower Miocene section of CRP-1 derive from at least three sources. A low-diversity but persistent angiosperm-moss-liverwort assemblage may reflect contemporaneous herb-moss tundra and a climate with summer temperatures similar to that of islands in the vicinity of the Antarctic Convergence today. More diverse *Nothofagus*-podocarp-*Proteaceae* assemblages at c. 70 mbsf and 100-116 mbsf may reflect woody vegetation growing nearby in warmer sites or periods, long distance transport, or redeposition from older strata. A contemporaneous local origin is preferred: although it is not possible to determine the precise form of this vegetation from palynological data, a conservative model with low-growing shrubs would imply July mean temperatures of at least 7°C. Reworked Permian-Triassic miospores are present in low numbers throughout the sequence. Pleistocene samples contain assemblages likely to have been reworked from older strata, mostly having similar taxa to the lower Miocene section, although one sample contains a *Nothofagus*-dominated pollen assemblage (also interpreted as reworked) similar to that of the Sirius Group of the Transantarctic Mountains.



INTRODUCTION

Cape Roberts Project drillhole CRP-1, sited in 153.5 m of water in the southwestern Ross Sea at 77.008°S and 163.755°E (see location map), was drilled in October, 1997. It forms part of a programme to obtain continuous core from Cenozoic and postulated Upper Cretaceous strata on the western margin of the Victoria Land Basin, in order to study the tectonic and climatic history of the region (Cape Roberts Science Team [CRST], 1998a). Poorly consolidated glaciomarine sediment plus a short mixed biogenic carbonate-clastic unit, dated at 1.25-1.80 Ma (early Pleistocene) from diatom biostratigraphy, was cored with good recovery from c. 20 m below sea floor to 43.55 mbsf (CRST, 1998b, 1998d). From this depth to the base of the cored sequence at 147.69 mbsf a cyclic sequence of shallow-water glaciomarine diamictites, sandstone and siltstone was penetrated. This section was dated at 17.5-22.4 Ma (early Miocene) from diatom biostratigraphy and magnetostratigraphy (CRST, 1998c, 1998d).

Palynological study of CRP-1 was conducted at McMurdo Station to assist in dating the sediments encountered, and in determination of their environment of deposition. Further aims included determination of sediment provenance from redeposited palynomorphs, description of new palynomorphs, construction of a biostratigraphic database as an aid to other Antarctic studies, and characterisation of terrestrial vegetation and environments from spores and pollen of land plants. Preliminary palynological results were presented in the initial detailed stratigraphic reports (CRST, 1998b, 1998c). This paper discusses the terrestrial palynomorph assemblages; the richer marine palynomorph flora is described by Hannah et al. (this volume) and Wrenn et al. (this volume). Detailed comparisons of fossil palynomorphs

with reference material of extant taxa and formal descriptions of new species are still in progress.

PALYNOLOGICAL PROCESSING AND EXAMINATION

Forty-five samples were processed at McMurdo Station using the method outlined in the Initial Report (CRST, 1998a) and by Simes & Wrenn (this volume), and three additional samples from the Quaternary section of the core were processed later using similar chemistry at Lower Hutt. Fossil taxa recognised from the Pleistocene and Miocene sections of CRP-1 are listed with authorities in table 1, to enable comparison of species composition; the nomenclature of some taxa has been revised from that reported in CRST (1998b, 1998c). The table lists total numbers of specimens observed during microscopic scanning of all of the organic residue recovered from samples. The small numbers of terrestrial palynomorphs recovered from CRP-1 are consistent with the low abundance of fossil pollen and spores (collectively termed miospores) previously observed in younger Cenozoic samples from the western Ross Sea and Victoria Land (e.g. Hall, 1975; Mildenhall, 1989; Askin & Ashworth, 1998). The low abundance is interpreted to be due principally to the limited extent of vegetation cover in the region during this period.

From the low abundance arises three difficulties for interpretation. Firstly, the composition of the palynoflora which is being sampled is rather imprecisely known, because of the statistical errors associated with small samples. Secondly, reworked miospores from older sediments may form a significant proportion of the assemblage, as discussed further below. Thirdly, contaminant miospores may assume a high relative abundance compared to those indigenous to the samples

themselves. It is important to recognise this potential source of misinterpretation, which is here more significant than is the usual case in sediments deriving from better vegetated regions which have a greater miospore production. In many of the Quaternary and Miocene samples small numbers of contaminant miospores were identified, despite care in laboratory cleanliness and location of the McMurdo laboratory remote from living plant sources. Autofluorescence of specimens using a Zeiss epi-illumination system III-RS with blue-violet excitation was used as an aid to discriminate contaminant modern pollen. Modern contaminant specimens could be recognised by their bright (white or greenish) autofluorescence and a combination of other features, including generally colourless or pale yellow exine and remnant protoplasm.

Contaminant taxa identified reflect the regions of origin of the equipment and personnel involved in the project, and presumably originate from dust adherent to packaging, equipment, and clothing: *Artemisia* and *Betula* from North America, and *Nothofagus* cf. *fusca* and *Dicksonia* from New Zealand. Pollen of taxa with cosmopolitan distribution was also identified: *Pinus*, Poaceae, and weeds associated with settlements and agriculture such as *Rumex* and *Haloragis*. A single *Pinus* pollen grain was identified from a glycerine-smear petri dish exposed in the laboratory for a week during processing. The drilling mud (a synthetic polymer) was also checked for contaminants and only modern Haloragaceae pollen (possibly of laboratory origin) were found. The *Lycopodium* tablets used for estimation of palynomorph concentration were also examined for purity: no contaminant miospores were encountered during a scan of approximately 17 000 grains of *Lycopodium clavatum* type in a control slide prepared from several dissolved tablets.

RESULTS

Autofluorescence assisted recognition of recycled Permian-lower Mesozoic miospores. These are noticeably deeper in colour than recognisable Cenozoic specimens, being yellow-brown to brown in transmitted light, and display little or no autofluorescence. Commonly, they are broken and have adherent deep brown organic material, perhaps from parent carbonaceous sediments or coals.

Undoubted Cenozoic miospores from the sequence are paler, generally yellow to light yellow-brown in transmitted light, and show a range of autofluorescence colours from yellow to orange, but no pattern of variation was distinguished. Less stratigraphically well-known taxa with similar autofluorescence were assigned to this group. Specimens are generally moderately well-preserved, and show little biogenic or diagenetic degradation or breakage.

REDEPOSITED BEACON SUPERGROUP MIOSPORES

Redeposited spores of probable Permian to early Mesozoic age are present in the three Pleistocene samples 36.62-42.41 mbsf, and throughout the Miocene section, notably around 70 m. They include taeniate and non-

taeniate bisaccate pollen and a variety of spores (Tab. 1, Fig. 2n & o). Opaque carbonaceous fragments, probably in part derived from Beacon Supergroup coal measures, are abundant. The limited oxidation applied to CRP-1 samples (10 minutes nitric acid digestion) probably restricted the number of miospores extracted from these fragments, compared to CIROS-1 and MSSTS-1 drillholes (located c. 60 km to the south of CRP-1; CRST, 1998d) in which an apparently greater diversity of reworked miospores were observed (Mildenhall, 1989; Truswell, 1986). *Granulatisporites trisinus* has been widely recorded from the Permian, but not the Triassic, of southern continents. Although other taxa such as *Equisetosporites* sp. do occur also in the Triassic, it is likely that many are derived from Permian strata of the Beacon Supergroup, which crops out extensively in the nearby Transantarctic Mountains.

PLEISTOCENE STRATA

Thirteen samples from the Pleistocene (0 to c. 43.55 mbsf) section of the CRP-1 core, including a sea floor sample, were processed. Very small numbers of Cenozoic miospores, mostly well-preserved, were found in nine of these. The 21.04 mbsf sample contained the most abundant miospores, the assemblage being dominated by pollen of *Nothofagidites lachlaniae* (Fig. 2g) closely comparable to that described from the Sirius Group of Oliver Bluffs (Transantarctic Mountains) by Hill & Truswell (1993). Single grains of a trisaccate gymnosperm pollen assigned to *Trichotomosulcites subgranulatus* (= *Podosporites microsaccatus* (Couper, 1953) Dettmann, 1963; see Mildenhall, 1994; Fig. 11) and a periporate angiosperm pollen, *Chenopodipollis* sp. were also seen.

Other miospores observed in the Pleistocene section of CRP-1 include (Tab. 1): *Nothofagidites flemingii*; *Nothofagidites* cf. *flemingii* (smaller than typical *N. flemingii*); other *Nothofagus* spp. of *fusca*-pollen type; the *brassii*-pollen type *Nothofagidites cranwelliae*; *Tricolpites* sp. a, a distinctive tricolpate pollen seen also in the Miocene section; a triporate angiosperm pollen probably referable to Proteaceae (Fig. 2f); and several species of podocarpaceous pollen, *Dacrydiumites praecupressinoides*, *Microcachryidites* sp., and *Podocarpidites* spp. Also present are hilate verrucate spores, *Coptospora* sp. b and *Coptospora* sp. c (Fig. 1e), comparable to spores of the moss family Bartramiaceae (Boros et al., 1993). These have a notable similarity to spores of *Conostomum*, e.g. *Conostomum pentastichum* illustrated by Barrow & Smith (1983) from Holocene peats of South Georgia. Truswell (1983, p. 145, Pl. 2, Figs. 4, 5 & 9) described similar (recycled) spores from modern marine sediments of the Ross Sea, comparing them with the larger spores of *Coptospora* sp. A of Dettmann (1963) from the Albian of the Otway Basin, southeastern Australia. The genus *Coptospora* Dettmann, 1963, is also used here for fossil bryophytic spores of this morphological type.

MIOCENE STRATA

Miospores are present in small numbers in most of the 35 samples from the lower Miocene section (Tab. 1). In

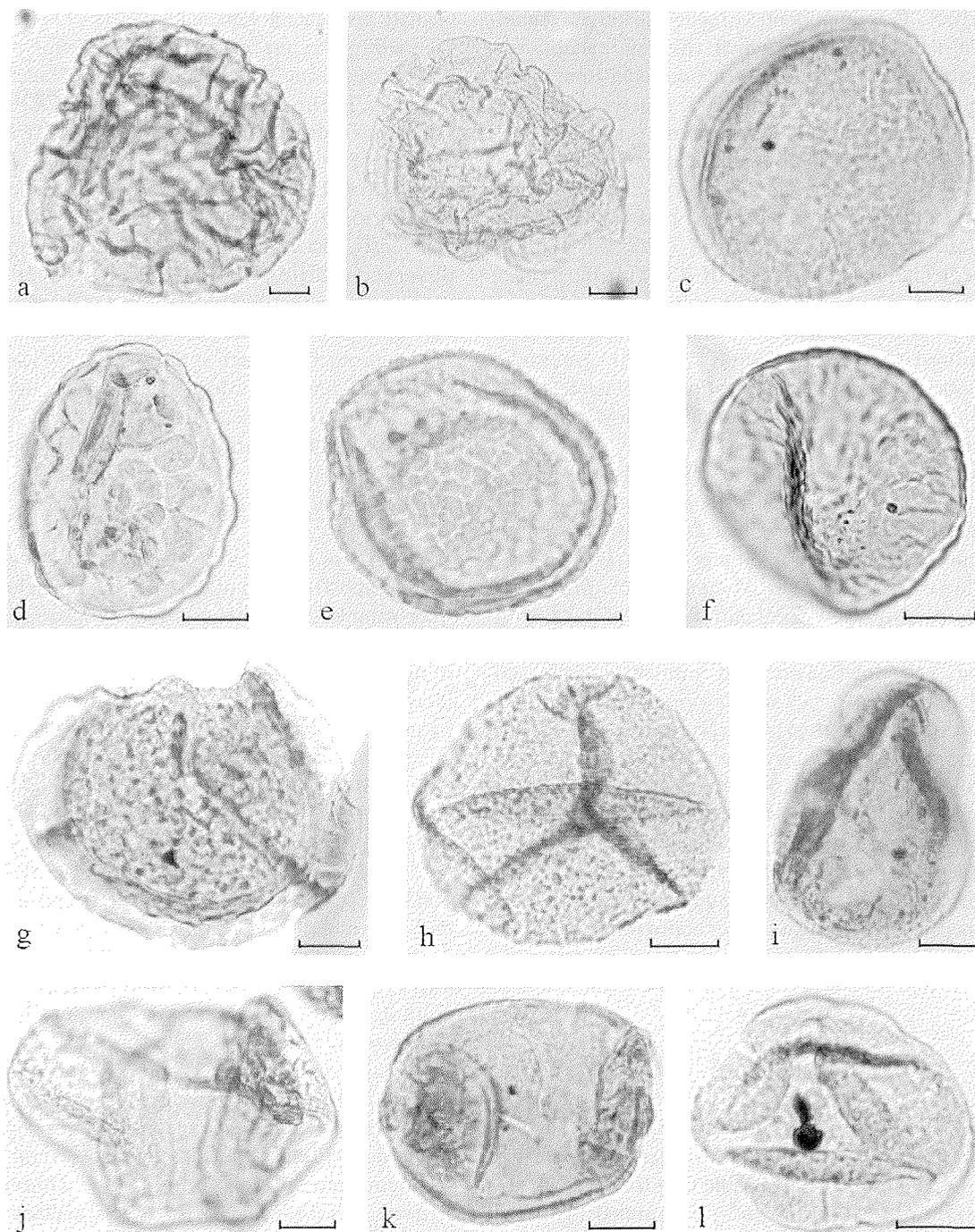


Fig. 1 - Selected miospores from CRP-1. Sample depths indicated are the top of the sample interval. Figures are at varied magnifications, size refers to maximum dimension; scale bar 10 μm . "Cenozoic" taxa: a) Marchantiaceae (size 88 μm , depth 99.02 mbsf, slide P12/2, England Finder coordinates C43/2); b) Marchantiaceae (73 μm , 58.43 mbsf, P18/2, J28/4); c) *Coptospora* sp. a (59 μm , 70.02 mbsf, P21/1, X43/0); d) *Coptospora* sp. b (43 μm , 70.02 mbsf, P21/1, W49/2); e) *Coptospora* sp. c (33 μm , 34.00 mbsf, P38/1, E28/1); f) *Coptospora* sp. c (41 μm , 112.44 mbsf, P33/1, Q39/0); g) *Aequitriradites* sp. (61 μm , 147.68 mbsf, P45/1, J32/1); h) *Baculatisporites* sp. (44 μm , 96.37 mbsf, P29/1, C39/3); i) *Dilwynites granulatus* Harris, 1965, folded specimen (46 μm , 67.54 mbsf, P20/1, T42/1); j) *Podocarpidites* sp. (61 μm , 116.45 mbsf, P34/1, X43/0); k) *Phyllocladites mawsonii* Cookson, 1947 ex Couper, 1953 (41 μm , 67.54 mbsf, P20/1, S40/0); l) *Trichotomosulcites subgranulatus* Couper, 1953 (33 μm , 21.04 mbsf, P4/1, M32/0).

contrast to the apparently monospecific Pleistocene sample from 21.04 m, Miocene samples contain a number of *Nothofagidites* species. With the exception of single specimens of *N. asperus* (*menziesii*-pollen type, Fig. 2j) at 116.45 and 120.27 m, all are of the *fusca*-pollen type, and include *N. flemingii* (Fig. 2h) and *N. lachlaniae* as well as other undifferentiated *fusca*-type species (Fig. 2i).

A distinctive and relatively constant element, prominent in some samples, is *Tricolpites* sp. a (Fig. 2a-c). This tricolpate angiosperm pollen has a tectate wall structure with prominent, commonly grouped columellae. It may be conspecific with *Tricolpites* sp. 2 of Truswell (1983) and pollen from the Sirius Group of Oliver Bluffs illustrated by Askin & Markgraf (1986) and compared by these authors

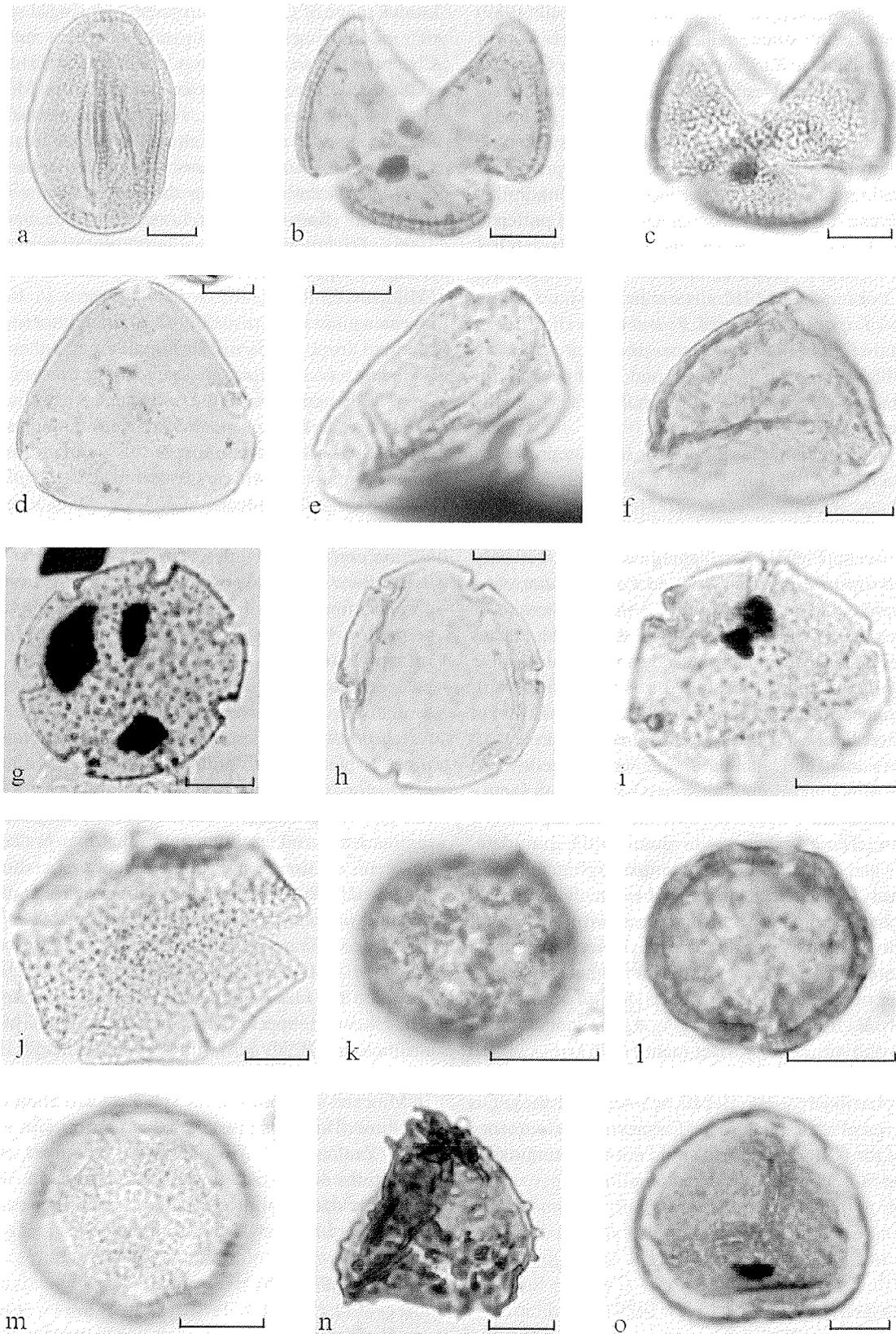


Fig. 2 - Selected miospores from CRP-1 (continued). Figures are at varied magnifications; scale bar 10 μm . "Cenozoic" taxa: a) *Tricolpites* sp.a. equatorial view (47 x 30 μm , 82.18 mbsf, P24/1, Y32/1); b & c) *Tricolpites* sp.a. polar view, two foci (40 μm , 85.36 mbsf, P25/2, F30/0); d) *Triporopollenites* sp. (47 μm , 70.02 mbsf, P21/1, C49/0); e) *Triporopollenites* cf. *T. ambiguus* Stover, 1973 (33 μm , 116.45 mbsf, P34/1, D37/0); f) triporate pollen cf. Proteaceae (33 μm , 34.00 mbsf, P38/1, M28/0); g) *Nothofagidites lachlaniae* (Couper, 1953) Pocknall & Mildenhall, 1984 (33 μm , 21.04 mbsf, P4/1, A52/3); h) *Nothofagidites flemingii* (Couper, 1953) PotoniĚ, 1960 (34 μm , 67.54 mbsf, P20/4, V45/0); i) *Nothofagidites* sp. (25 μm , 116.45 mbsf, P34/1, Y42/0); j) *Nothofagidites asperus* (Cookson, 1959) Romero, 1973 (45 μm , 116.45 mbsf, P34/1, X44/0); k & l) *Chenopodioidites* sp., two foci of same specimen (21 μm , 99.02 mbsf, P12/1, T47/4); m) Caryophyllaceae (27 μm , 82.18 mbsf, P24/2, T49/0). Redeposited Permian-lower Mesozoic taxa: n) *Horriditriteles ramosus* (Balme & Hennelly, 1956) Bharadwaj & Salujha, 1964 (31 μm , 99.02 mbsf, P12/2, W46/0); o) *Punctatisporites* sp. (38 μm , 108.75 mbsf, P32/2, P48/0).

with that of Polygonaceae or Labiatae. Mildenhall (1989) referred apparently similar pollen from the lower part of CIROS-1 drillhole to *Perforicolporites digitatus* Guzman, but the CRP-1 pollen does not have digitate columellae.

Other angiosperm taxa include *Chenopodipollis* sp. (Fig. 2k-l) similar to that seen in the Quaternary section, and a slightly larger but morphologically similar periporate pollen distinguished as Caryophyllaceae (Fig. 2n). Pollen of Proteaceae is represented by an aggregate of pollen at 9902 mbsf, and single grains of *Triporopollenites* sp. (Fig. 2d; in CRST, 1997c compared with *Proteacidites parvus* Cookson, but the latter is smaller and has straight sides) and *Triporopollenites* cf. *T. ambiguus* (Fig. 2e) at 116.45 mbsf. The last two specimens are closely comparable to *Triporopollenites* sp. and *Triporopollenites* cf. *T. ambiguus* illustrated by Mildenhall (1989) from the lower part of the CIROS-1 sequence.

Coniferous pollen is less abundant, and is represented by *Podocarpidites* spp. (Fig. 1j), *Phyllocladidites mawsonii* (Fig. 1k) and *Microcachryidites* cf. *M. antarcticus*, all of Podocarpaceae affinity, and *Dilwynites granulatus* (Araucariaceae, Fig. 1i). Fern spores are represented only by *Baculatisporites* sp. (Fig. 1h) and *Polypodiidites* sp.

Bryophytic spores comprise a distinctive element of the Cenozoic palynoflora. Marchantiaceae (Hepaticae) are represented at several horizons by an apparently alete (possibly hilate) spore with folded exoexine (Fig. 1a-b), similar to spores of *Clevea robusta* illustrated by Erdtman (1957), and *Bucegia romanica* illustrated by Boros et al. (1993). As noted above, hilate spores with single layered wall structure, and resembling spores of the moss family Bartramiaceae, have been referred to the genus *Coptospora* Dettmann. Three species with dominantly granulate, verrucate and coarsely verrucate sculpture (Fig. 1c, f & d respectively) have been distinguished in the Miocene section, but specimens vary in coarseness of sculpture, and the diversity may easily be greater. Folded specimens of the more coarsely verrucate species might be mistaken for spores of *Polypodiidites* Couper. *Aequitridites* sp., recorded only from 147.68 mbsf (Fig. 1g), is another taxon with bryophytic affinity. Dettmann (1963) has noted similarity of spores of this genus to those of the extant family Sphaerocarpaceae (Hepaticae). Although the genus is more typical of the Jurassic and Cretaceous, fluorescence colour of the CRP-1 specimen could not be distinguished from that of undoubted Cenozoic taxa.

DISCUSSION

PLEISTOCENE STRATA

The relative abundance of *Nothofagidites lachlaniae* in the 21.04 mbsf assemblage is similar to that reported from the Sirius Group in the Transantarctic Mountains (Askin & Markgraf, 1986; Hill & Truswell, 1993). *Chenopodipollis* sp. is similar to *Chenopodipollis chenopodiaceoides* (Martin) recorded from the Oligocene section of CIROS-1 and referred to the Chenopodiaceae family by Mildenhall (1989). The latter species has a

known range of Oligocene to present. A single specimen of morphologically similar pollen, noted as Chenopodiaceae, has been reported from the Sirius Group of the Reedy Glacier area of the Transantarctic Mountains (R.A. Askin, pers. comm.). The pollen is also similar to that of one of the two extant Antarctic vascular plants, *Colobanthus quitensis*, a cushion plant member of the Caryophyllaceae inhabiting the Antarctic herb tundra formation (Barrow, 1976; Longton, 1985; Sadowska, 1998). *Trichotomosulcites subgranulatus* was reported from the upper Eocene section of CIROS-1 drillhole (Mildenhall, 1989), and is also frequent in Ross Sea marine sediments (Truswell, 1983), but has not so far been reported from the Sirius Group although other taxa of podocarpaceous affinity are known to be present. Known range of the species in New Zealand and Australia is Early Cretaceous to Palaeogene. Whether contemporaneous or (likely) reworked, the miospore assemblage reflects a vegetation of limited diversity dominated by *Nothofagus*.

The other Pleistocene samples contain very sparse miospore assemblages similar to those of the Miocene section, containing mainly Cenozoic species. No significant difference in miospore abundance or taxonomic composition is noted from the biogenic carbonate-rich sequence between 31.89 and 33.82 mbsf despite interpretations, from sedimentology and marine palaeoecology (CRST, 1998d, p. 134), that this represents a relatively sea-ice free and warmer period. Extremely rare *Nothofagus* pollen at apparently the most favourable time for plant growth in the period supports a reworked origin for *Nothofagus* pollen in the higher, 21.04 mbsf sample. The other Cenozoic taxa present may represent a similar terrestrial environment to that interpreted for the Miocene section, as discussed below, but are likely reworked from Miocene or older sediments. *Nothofagidites cranwelliae*, one of the *brassii*-pollen group of *Nothofagus*, occurs at 33.72 mbsf. This species was not observed in the Miocene section of CRP-1, although Truswell (1986) recorded the *brassii*-pollen type in the lower to middle Miocene and upper Oligocene sections of MSSTS-1 drillhole, and Brady & Martin (1979) and Jiang & Harwood (1993) reported other *Brassospora* subgenus pollen species in Miocene sediments of the sub-Ross Ice Shelf RISP J-9 drillhole. This subgenus of *Nothofagus* became extinct in New Zealand and Australia with the onset of colder conditions during the Pliocene. Its survival in Antarctica to a later date would be surprising, and the specimen is almost certainly reworked from older strata.

MIOCENE STRATA

Discrimination of post-Triassic redeposited miospores is critical to the interpretation of the CRP-1 lower Miocene miospore sequence. The Jurassic to Early Cretaceous species *Murospora florida* (Balme) and *Callialasporites trilobatus* (Balme) were recorded in MSSTS-1 drillhole by Truswell (1986), and *Classopollis classoides* (Pflug) in CIROS-1 by Mildenhall (1989). Although some of the taxa here classed as "Cenozoic" first appear in the Mesozoic, none are definitely restricted to pre-Miocene

strata elsewhere. Miospore-bearing Lower Jurassic sediments are known from the Transantarctic Mountains (Norris, 1965), and are a possible source for some of the MSSTS-1 and CIROS-1 miospores. The lack of a definite Late Cretaceous component is consistent with Truswell's (1983, p. 126-127) finding that possible Late Cretaceous palynomorphs are rare in modern sediments of the western Ross Sea, and that species restricted to that period are absent.

No precise age assessment can be made from known lower range limits of the Cenozoic miospore taxa, though *Chenopodipollis* spp. are not known from pre-Oligocene strata in Australia or New Zealand (Mildenhall, 1989), and current though limited data suggest Oligocene and younger age in Antarctica for this pollen type. Other taxa, where known, first appear in Eocene or older strata. The occurrence of rare specimens of Eocene-early Oligocene dinoflagellates in CRP-1 Miocene samples indicates that concurrent redeposition of miospores of similar age is possible. There is, however, no obvious correspondence between occurrences of these dinoflagellates and diversity/abundance of, for example, *Nothofagidites* spp., and the absence of pollen of the *Nothofagus brassii*-type, common in Eocene erratics of McMurdo Sound (McIntyre & Wilson, 1966) suggests that redeposited miospores of this age do not form a significant component of the palynoflora.

The upper range limits of most taxa are very poorly known in the Antarctic region. The limited data from the Sirius Group suggest most of the *Nothofagus*, Proteaceae and conifer species had disappeared by the Pliocene (e.g. Askin & Markgraf, 1986; Hill & Truswell, 1993), or possibly earlier, if the Pliocene dating of the Sirius Group is not accepted (e.g. Burekle & Pokras, 1991; Stroeven et al., 1998). Points of similarity with the Sirius assemblages include the presence in both of podocarp pollen, *Tricolpites* sp. a (the Polygonaceae or Lamiaceae pollen of Askin & Markgraf, 1986), *Chenopodipollis* sp., *Coptospora* spp., and the cavate spore referred to Marchantiaceae (R.A. Askin pers. comm.). However, the CRP-1 Miocene assemblage differs from those reported from the Sirius Group in having greater diversity, notably in *Nothofagidites* species. Within *Nothofagidites*, the CRP-1 assemblages do not show the dominance of pollen of *N. lachlaniae* type seen in the Sirius Group.

In a search for evidence that could corroborate the Pliocene dating of the Sirius Group *Nothofagus* fossils, Fleming & Barron (1996) extracted miospore assemblages from Pliocene sediments at DSDP Site 274. In the three richest samples, dated to c. 3.0 Ma, a clear dominance of *Nothofagidites* cf. *N. lachlaniae* contrasts with the lower relative abundance of this species in assemblages reported by Truswell (1983) and Truswell & Drewry (1984) from surficial sediments in the Ross Sea. Fleming & Barron (1996) conclude that the miospore assemblage at Site 274 was therefore not redeposited from older sediments, but probably derived from *Nothofagus* living in Antarctica during the mid Pliocene. Other taxa recorded in their samples include other pollen referable to the *fusca*-pollen type of *Nothofagus*, a variety of Podocarpaceae and Araucariaceae pollen, a single species attributable to Proteaceae, *Coptospora* sp., and a few other angiosperm

pollen taxa and cryptogam spores of uncertain affinity.

In MSSTS-1 drillhole Truswell (1986) recorded sparse miospores from the Quaternary, Pliocene, lower to middle Miocene, and upper Oligocene sections. She concluded that the sparseness of the assemblages indicated that nearby land did not support extensive vegetation after the Oligocene. Since at least some of the Cretaceous-Cenozoic component was reworked from Eocene strata, however, the date of decline or elimination of vegetation in this part of Antarctica could not be clearly seen. The occurrence of *Myricipites harrisii* (Couper) and *Nothofagidites* of the *brassii*-type throughout the MSSTS-1 sequence are points of difference with the CRP-1 Miocene assemblages, and suggest that redeposited Eocene-Oligocene miospores may have been more prevalent at the MSSTS-1 site.

The RISPJ-9 miospore assemblage recorded by Brady & Martin (1979) and later in more detail by Jiang & Harwood (1993), is also reported to contain a variety of *Nothofagidites* species of the *brassii*-type, which according to the latter authors is present in approximately equal proportions to that of *fusca*-type. Another difference from the CRP-1 assemblage is the presence of pollen of Myrtaceae (although this was recorded only by Jiang & Harwood). Brady & Martin's material, initially considered to be of middle Miocene age mainly on the basis of diatom biostratigraphy, consisted of the sediment matrix. Kellogg & Kellogg (1986) later re-examined diatom assemblages from the sediment matrix and concluded that the presence of certain species indicated the sediments had been reworked during the Pliocene and Pleistocene. However, Jiang & Harwood's material consisted of selected marine diatomite clasts of early Miocene age, and these authors concluded that their miospore assemblage reflected penecontemporaneous vegetation.

Mildenhall (1989) considered that much of the CIROS-1 miospore assemblage was contemporaneous with sedimentation, although some could be redeposited from Eocene or Palaeocene strata. Contemporaneity was supported by the occurrence of *Chenopodipollis*, by the presence of pollen aggregates suggesting deposition of anthers and therefore a nearby vegetation source, and by the occurrence of a *Nothofagus* leaf in the upper part of the Oligocene section at 215 m (Hill, 1989). The CRP-1 assemblage, although apparently more restricted, has many taxa in common with that of CIROS-1. An aggregate of Proteaceae pollen occurs in CRP-1 at 99.02 mbsf. Unfortunately the stratigraphic distribution of taxa in CIROS-1 has not so far been tabulated, limiting detailed biostratigraphic comparison, although the leaf described by Hill (1989) is of subgenus *Fuscaspora* affinity, and Mildenhall (1989) reported that *fusca*-type pollen, including aggregates suggestive of anthers, dominated other *Nothofagus* pollen types in the Oligocene section of the drillhole.

Inspection of table 1 suggests that it may be possible to distinguish two sources of Cenozoic miospores in CRP-1. Several *Nothofagidites* spp., *Podocarpidites* spp., and a range of angiosperm species occur relatively abundantly at 70.02 mbsf and between 100 and 120 mbsf. This assemblage could be interpreted to represent a *Nothofagus*-

dominated vegetation with a variety of other woody plants. Another component, comprising *Coptospora* spp., Marchantiaceae, and especially *Tricolpites* sp. a, is more consistently present through the sequence. Both this consistency and the relatively high frequency of *Tricolpites* sp. a in some samples suggests that it may be derived from a local vegetation of low diversity. Although Gramineae, characteristic of vegetation in the modern Subantarctic zone, are absent, this local vegetation may have been similar in form to that of the present-day herb tundra of the Cool to Cold Antarctic zones distinguished by Greene (1964). This tundra, rich in bryophytes but with a low diversity of non-woody vascular plants, is present in the coastal Antarctic Peninsula, and islands near or within the boundary of the Antarctic Convergence. If this vegetation represents a climatic climax, then the *Nothofagus*-dominated vegetation may represent warmer climatic intervals during the period represented by the Miocene sediments, long-distance transport (perhaps from West Antarctica), or reworking from Oligocene and/or Eocene strata.

Redeposition of miospores from older sediments cannot be entirely ruled out, but redeposition of more than a small proportion of miospores is discounted for the reasons outlined previously. Long-distance aerial transport is known to occur in the present Antarctic environment (Smith, 1991), and contributes considerable proportions of South American *Nothofagus* and other pollen and spores to modern terrestrial sediments in the Atlantic Subantarctic. The absence of miospores in many modern sediments of the McMurdo region, including the surface sample from CRP-1, suggests that a South American source is unlikely, but the possibility of a distant source cannot be entirely discounted because Tasmania would have been closer to the Ross Sea region in the Miocene (Lawver et al., 1992), and also because the islands of West Antarctica may have been partially vegetated during the Miocene.

Accepting Fleming & Barron's (1996) conclusions in support of the age of the Sirius Group plant fossils, and the CIROS-1 results, there is now good evidence for woody vegetation in the Transantarctic Mountains from the Pliocene and the Oligocene. The proposition that the early Miocene spore-pollen assemblage of CRP-1 includes a component derived from contemporaneous woody vegetation on the nearby coast therefore seems reasonable. It remains to consider further the possible nature of this vegetation and its climatic significance.

Anatomical study of wood and leaves of *Nothofagus beardmorensis* Hill et al. from the Sirius Group led Francis & Hill (1996) to conclude that the plants were deciduous dwarf trees of prostrate habit with branches that spread across the ground surface. In contrast, Mildenhall (1989) suggested that the diversity of *Nothofagus* pollen taxa present in the CIROS-1 sediments, and the resemblance of a considerable proportion to *N. dombeyi* (Mirb.), a temperate rainforest tree of southern South America, indicated that forest rather than shrubland existed along the coastline in the Oligocene. The diversity of *Nothofagus* pollen present in the CRP-1 Miocene sediments is more closely comparable to that of the CIROS-1 Oligocene, as

is the presence of Proteaceae pollen. However, the diversity of the Pliocene flora may be underestimated from the Sirius Group sites, which probably have a local provenance. Sediments which derive miospores from a wider region and range of plant habitats could be expected to show greater diversity, and in fact Fleming & Barron (1996) record a greater diversity of *Nothofagus* pollen in the Pliocene sediments of DSDP Site 274 than so far reported from the Sirius Formation.

The alpine and subalpine vegetation of Tasmania and southeast Australia includes a number of shrubby Proteaceae (e.g. *Orites*) and Podocarpaceae (e.g. *Lagarostrobos franklinii* Quinn, which has pollen with the morphology of *Phyllocladidites mawsonii*, occurs as a krummholz form in Tasmania), and a number of *Nothofagus* species are principal timberline trees and known as krummholz above the local treeline in Tasmania, New Zealand and South America. It is thus possible that the early Miocene vegetation may have resembled that of the Pliocene Sirius Formation, but differing only in a slightly greater diversity. The low abundance of miospores in the sediments would seem to better fit such a limited vegetation cover than the forested Oligocene landscape proposed by Mildenhall (1989). A mosaic of vegetation is likely to have existed, with low-growing *Nothofagus*-podocarp-Proteaceae scrub occupying warmer sites, for example on mid-slopes, and herbaceous or mossy tundra colder sites at higher elevations and on valley floors. Moisture availability would also influence the development of mosaic vegetation.

Given a suitable substrate and sufficient moisture, vascular plant growth at polar and altitudinal limits is principally limited by growing season temperature. The survival of plants in cold conditions may be appreciably enhanced by favourable snow blanketing, which can serve to insulate from extreme winter temperatures. Comparison with climatic data for the present day (Longton, 1988) suggests that vegetation beyond the poleward limit of extensive shrubland but with important flowering plants and profuse bryophytes, would imply mean July temperatures at sea level of at least 1–2°C but probably less than 7°C. Partial cover of low-diversity woody vegetation, but beyond the limit of extensively developed woodland would suggest mean July temperatures of at least 7°C, but less than about 10°C. Francis & Hill (1996) suggested that the dwarf growth forms of *Nothofagus beardmorensis* in the Meyer Desert Formation of the Sirius Group may have grown in summer temperatures around 5°C or even higher, although winter temperatures could have been as low as -15 to -22°C, and mean annual temperature about -12°C. These inferences depend on plant response to climate similar to that of today, although higher atmospheric CO₂ levels prior to the Pleistocene may have permitted growth of woody plants at lower temperatures than those which today limit their distribution (cf. Creber & Chaloner, 1985). Nevertheless, the vegetation and climatic interpretation would appear to be consistent with sedimentary facies analysis (Powell et al., this volume), which suggests that the glaciomarine Miocene sediments of CRP-1 were deposited close to a

grounded ice margin associated with abundant meltwater, in a polythermal glacial regime similar to that of modern Spitzbergen and southern Greenland.

While it is impossible to determine the form of the early Miocene vegetation from pollen data alone, interpretation of the latter should be aided by further study of the morphology of the fossil pollen and spores with the aim of identifying close relatives in the modern flora of the Subantarctic and southern cool temperate regions. Given sufficiently abundant palynomorph assemblages, statistical techniques such as association analysis may also in future shed light on the vanished plant communities of Antarctica.

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