

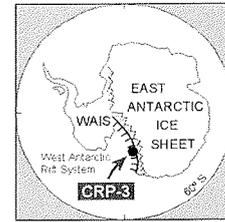
Oligocene and Early Miocene Phytoliths from CRP-2/2A and CRP-3, Victoria Land Basin, Antarctica

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Abstract - Phytoliths (siliceous plant microfossils) have been recovered from Cenozoic sediments (*c.* 34 to 17 Ma) in the CRP-2/2A and CRP-3 drillholes cored off Cape Roberts, Victoria Land Basin, Antarctica. The phytolith assemblages are sparse, but well-preserved and dominated by spherical forms similar to those of modern trees or shrubs. Rare phytoliths comparable to modern grass forms are also present. However, due to the paucity of phytolith data, any interpretations made are necessarily tentative. The assemblages of CRP-2/2A and the upper *c.* 250 m of CRP-3 are interpreted as representing a predominantly woody vegetation, including *Nothofagus* and *Libocedrus* with local areas of grass in the more exposed locations. A cool climate is interpreted to have prevailed throughout both cores. However, beneath *c.* 250 metres below sea floor in CRP-3, the dominant woody vegetation is supplemented by pockets of *Palmae*, *Proteaceae* and 'warm' climate grasses. This association represents vegetation growth in sheltered, moist sites – possibly north-facing mid-slopes or the coastal fringe. It may also represent remnant vegetation that grew in moist, temperate conditions during the Middle to Late Eocene, previously interpreted from the Southern McMurdo Sound erratics and lower part of the CIROS-1 drillhole. The phytolith analysis compares well to the terrestrial palynomorph record from both cores and provides additional independent taxonomic and climatic interpretations.



INTRODUCTION

The Cape Roberts Project is an international co-operative drilling programme to investigate the previously poorly constrained climatic and tectonic history of the East Antarctic Ice Sheet and the West Antarctic Rift System between Neogene and Palaeogene times. During the summer seasons of 1997-1999, three sediment cores were recovered from the seabed between 13 and 16 km off Cape Roberts (77.0°S, 163.7°E) on the western coast of McMurdo Sound, Antarctica (Fig. 1). Each hole was drilled into eastward-dipping strata and positioned to recover a continuous stratigraphic sequence with minimal overlap. The first core (CRP-1) reached 148 mbsf (metres below sea floor) before drilling was terminated when a storm blew out the fast ice near the drilling rig. The following season, 624 m of sediment was recovered in CRP-2/2A, which overlapped approximately 31 m with the base of CRP-1. CRP-3, drilled in 1999, is estimated to underlap CRP-2/2A by a few tens of metres and reached 939 mbsf. Drilling was halted within Devonian Beacon Sandstone below an unconformity of *c.* 300 million years at 823 mbsf. The entire Cenozoic sedimentary succession dates between *c.* 34 and 17 Ma, with an average core recovery of 95% in

CRP-2/2A and 97% in CRP-3 (Cape Roberts Science Team (CRST), 1998, 1999, 2000).

This study contributes to our knowledge of the Oligocene and Early Miocene climatic history of the western McMurdo Sound region by reconstructing the broad composition of coastal vegetation during the deposition of CRP-2/2A and CRP-3 using the siliceous plant microfossil (phytolith) record. The analysis expands on a preliminary study of phytoliths extracted from the Early Miocene to Quaternary sedimentary sequences of CRP-1 (Carter, 1998a) and extends current knowledge of Antarctic phytoliths. The study also highlights the value of phytolith analysis in terrestrial palaeoecological studies and includes the description of several new forms that have the potential to further refine climatic and taxonomic interpretations in the future.

Phytoliths are deposits of opal-silica precipitated within and between some cells of most living plants. When the plant dies, the organic material decomposes, releasing phytoliths into the soil and providing an *in situ* record of the vegetation cover. The silica grains may be directly entrained into the sediment or transported either by water or air to the site of final deposition. Phytoliths are particularly abundant in soils and loess deposits, but have been recognised as far back as the late Devonian in

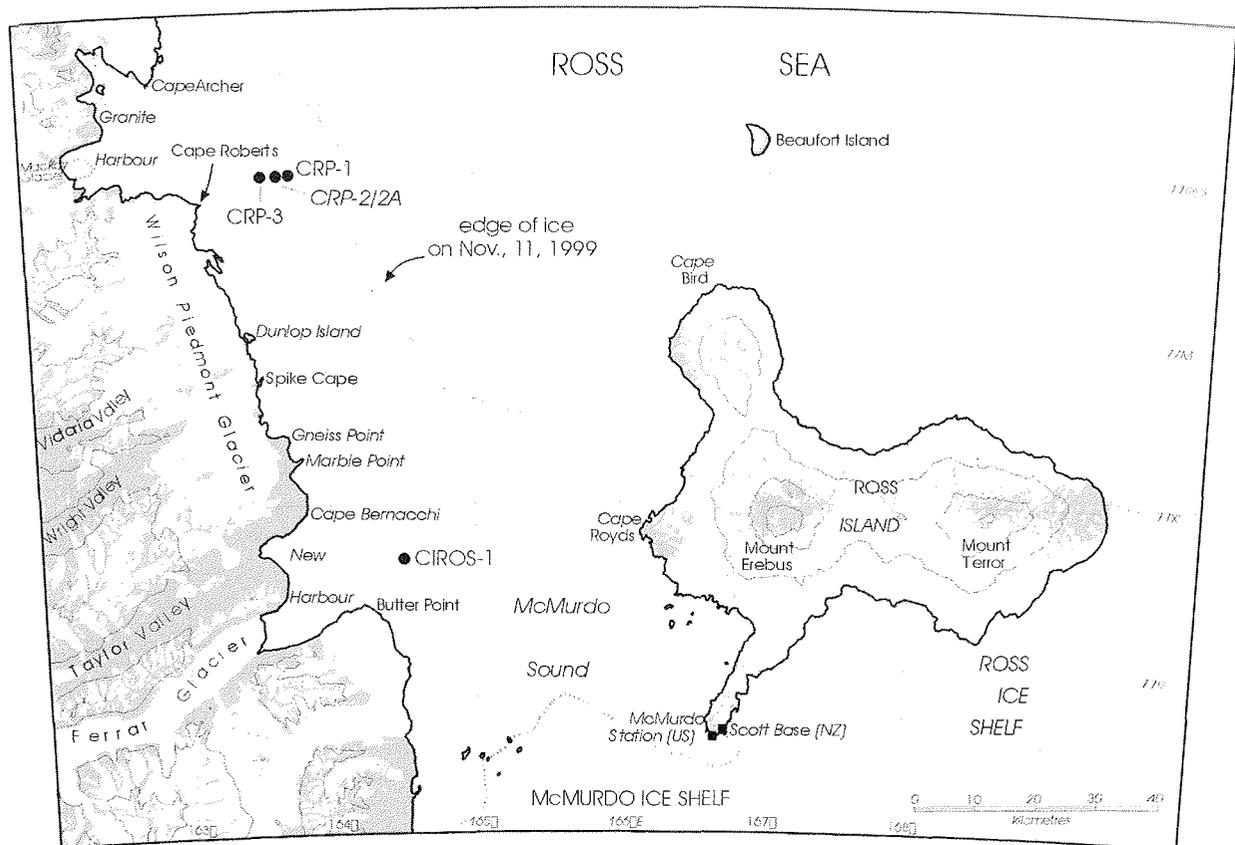


Fig. 1 - Map of the McMurdo Sound region of the Ross Sea, Antarctica, showing the CRP-1, CRP-2/2A and CRP-3 drill-sites off the coast of Cape Roberts (Cape Roberts Science Team, 1998, 1999, 2000) and the CIROS-1 drill-site off Butter Point (Barrett, 1989).

Antarctic Beacon Supergroup sediments (Carter, 1999).

A relatively new subject of micropalaeontology, opal phytolith forms have now been described from many regions of the world. Several significant contributions during the past decade include the publication of modern regional reference collections (for example, Kondo et al., 1994; Piperno & Pearsall, 1998; and Runge, 1999). Such detailed morphological studies are essential for the identification of original plants from disarticulated fossil material and the enhancement of palaeoecological interpretations. Despite the challenges of 'multiplicity' (the production of several different phytolith forms within a single plant species) and 'redundancy' (similar phytolith forms being produced by several species) (Rovner, 1971), many disaggregated phytoliths can be used to identify the original plants to family (*e.g.* Kealhofer & Penny, 1998), occasionally generic or even species levels (*e.g.* Piperno, 1985, 1988; and Piperno & Pearsall, 1998). Documentation has focussed on the description and classification of modern grass phytoliths, but extensive studies are now being completed on non-grass phytoliths. For example, Bozarth (1992) has described phytoliths from 82 species of North American dicotyledonous plants. Diagnostic dicotyledonous phytoliths were

produced by all but four of the species studied.

Despite the impressive body of published material, there remain divided opinions as to the most appropriate approach for opal phytolith description and classification. Three main methods have been used, which I will review below (based on Mulholland & Rapp, 1992): parataxonomic, morphological, and anatomical. The parataxonomic method follows the Linnean system, as expressed in the International Code for Botanical Nomenclature (ICBN), which assigns binomial names to morphologically distinct, dispersed phytoliths. Phytoliths are described solely on the basis of morphology, with no mention of the original plant, and are grouped following the rules of parataxa (Bukry, 1979). Ehrenberg (1854) originally described over 90 "species" using this method and in more recent times Dumitrica (1973) described three paragenera of Gramineae and one of Equisetales. This approach is now rarely used since phytoliths can often be identified to family or lower levels, as discussed above, and with ongoing studies it is being proven that there is more morphological range and consistency in production of phytoliths than first thought (*e.g.* Brown, 1984; Piperno, 1984).

The anatomical method of phytolith classification is preferred by botanists who study phytoliths within

tissue masses which provide much information about the specific location and orientation of certain forms within the original plant, as well as morphological details. Many authors exemplify this method, for example, Metcalfe (1960) (grasses), Metcalfe (1971) (sedges) and Miller-Rosen (1992) (cereal and date palm phytoliths). However, archaeological and geological workers do not readily use this form of classification as it is not applicable to dispersed phytoliths. Further, where tissue fragments are available, the surrounding cells often obscure the three-dimensional form of the phytoliths.

The morphological method of phytolith description and classification is in common use by archaeological and geological researchers. Phytoliths are described using purely morphological terms and assigned either geometric descriptors based mainly on outline shape, or anatomical descriptors related to the location of production in the plant. Twiss, Suess & Smith (1969) provided the first widely applied morphological/geometric approach for classifying disaggregated grass phytoliths which has been used and expanded in many studies (*e.g.* Lewis, 1981; Brown, 1984; Fredlund, Johnson & Dort, 1985; Mulholland & Rapp, 1985, 1992; Ollendorf, 1992; Twiss, 1992). Study-specific morphological classifications have also been published, for example, Runge (1999) described soil phytoliths from tropical rainforest and grassland habitats in central Africa and created her own classification using seven main categories and several sub-categories. More generalised keys have also been described, including a hierarchical classification of standard types, using photographic aids, for the Palaeoethnobotany Laboratory of the University of Missouri-Columbia (Pearsall & Dinan, 1992). In an attempt to begin standardising the description and classification of phytoliths world-wide, Bowdery *et al.* (2001) have described the basis of a universal phytolith key with standardised terms for surface ornamentation. This is the first of a planned series of papers describing keys for identification of disarticulated phytoliths based on eight basic shape categories. Finally, a combined morphological/anatomical approach relates phytolith morphology to the context within the plant and assigns names accordingly, for example, long cylindrical forms may be called 'sclereids' or 'tracheids' (Mulholland & Rapp, 1992). Piperno (1988) advocates this approach, which simplifies the interpretation of fossil material, for example, the presence of sclereids in the phytolith assemblage indicates woody plants, even without species identification.

Fossil phytoliths are becoming increasingly useful for the reconstruction of palaeoclimates. Where fossil phytoliths are directly comparable to modern analogues, extrapolation of the extant plant's preferred growing conditions to the fossil record allows a broad interpretation of contemporaneous onshore source

vegetation and climate. In addition, burial and diagenetic conditions are not as crucial for the good preservation of phytoliths as for organic-walled plant microfossils. Therefore, phytolith analysis can augment vegetation models derived from established techniques of terrestrial palynomorph analysis. However, it is important to note that, particularly with phytolith and terrestrial palynomorph interpretations, there are no exact modern analogues of Tertiary species (Hill & MacPhail, 1983), so comparisons with climatic preferences of extant plants are made tentatively. Further, soil processes as well as burial dissolution can affect phytolith assemblages following separation from the originating plants. The relative density and morphology of the phytolith grains can also affect transport to the site of deposition. These important factors drastically affect the interpretation of phytolith assemblages.

METHODS

Phytoliths were extracted from CRP-2/2A and CRP-3 sediment samples using a combination of methods described by Piperno (1988) and Hart (1988) and refined by Carter (1998a, 1998b). Each sample underwent an initial oxidation treatment using hydrogen peroxide and was disaggregated using an ultrasonic probe. The fraction coarser than 250 μm was removed by filtration, and clay particles removed by decantation. The sample was then treated with Schulze's solution to remove the remaining organic matter and centrifuged in sodium polytungstate solution (specific gravity 2.3). Siliceous residue containing phytoliths was pipetted from the surface of the supernatant and one microscope slide prepared per sample using Canada Balsam as the mounting medium. Millipore-filtered water was used throughout the procedure and efforts were made to prevent contamination. Each slide was scanned in its entirety at 500x magnification for estimates of abundance, and at 1000x for detailed morphological examination. A tally was taken of each distinct morphology to provide an overall impression of the abundance and morphological diversity.

Twenty-one samples of fine-grained lithologies, each weighing approximately 10 g were processed from CRP-2/2A. The samples were spaced at an average of 30 m, between 27.99 and 623.03 mbsf. CRP-3 samples were processed from fine-grained sediment initially crushed and disaggregated in water for diatom analysis at Cray Lab, McMurdo Station. Twenty-seven samples, each weighing *c.* 5 g, were processed for phytolith extraction between 2.85 and 781.26 mbsf - at *c.* 10 m intervals from the upper 100 m and at *c.* 50 m intervals below that level. Prior to phytolith extraction procedures, the CRP-3 samples had been centrifuged and dried to remove water. Despite sparse phytolith occurrence, sample-to-sample

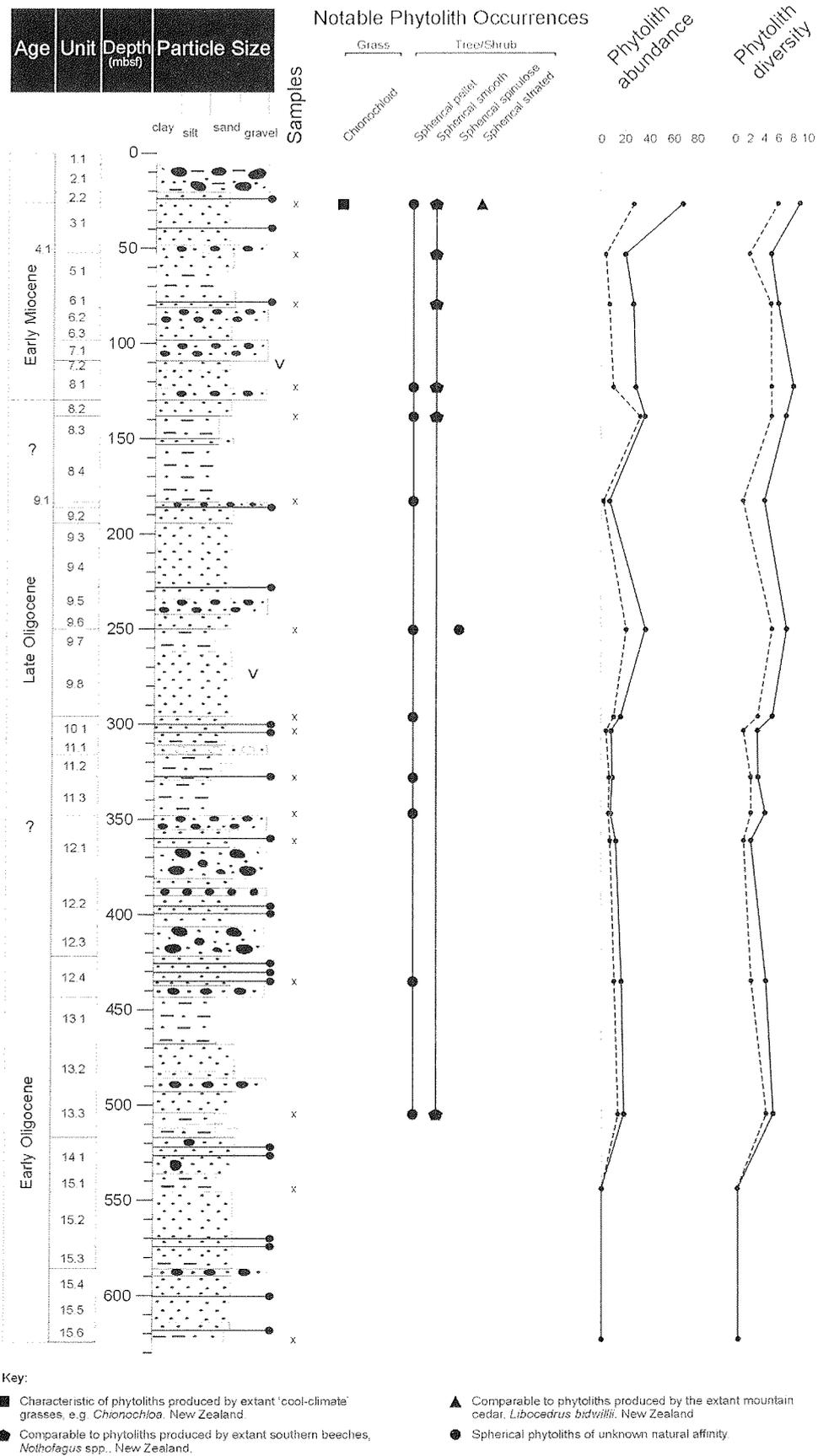


Fig. 2 - CRP-2/2A notable phytolith occurrences, abundance and diversity. 'Notable Phytolith Occurrences': points represent actual occurrences with joining lines indicating observed range. Note: joining lines are not intended to imply continuous presence; different shaped bullets are classified in the key. 'Phytolith Abundance' and 'Phytolith Diversity' represent the absolute number of specimens and number of classes encountered, respectively, during a complete scan of one slide per sample. Dashed lines represent the spherical class only; solid lines represent all classes.

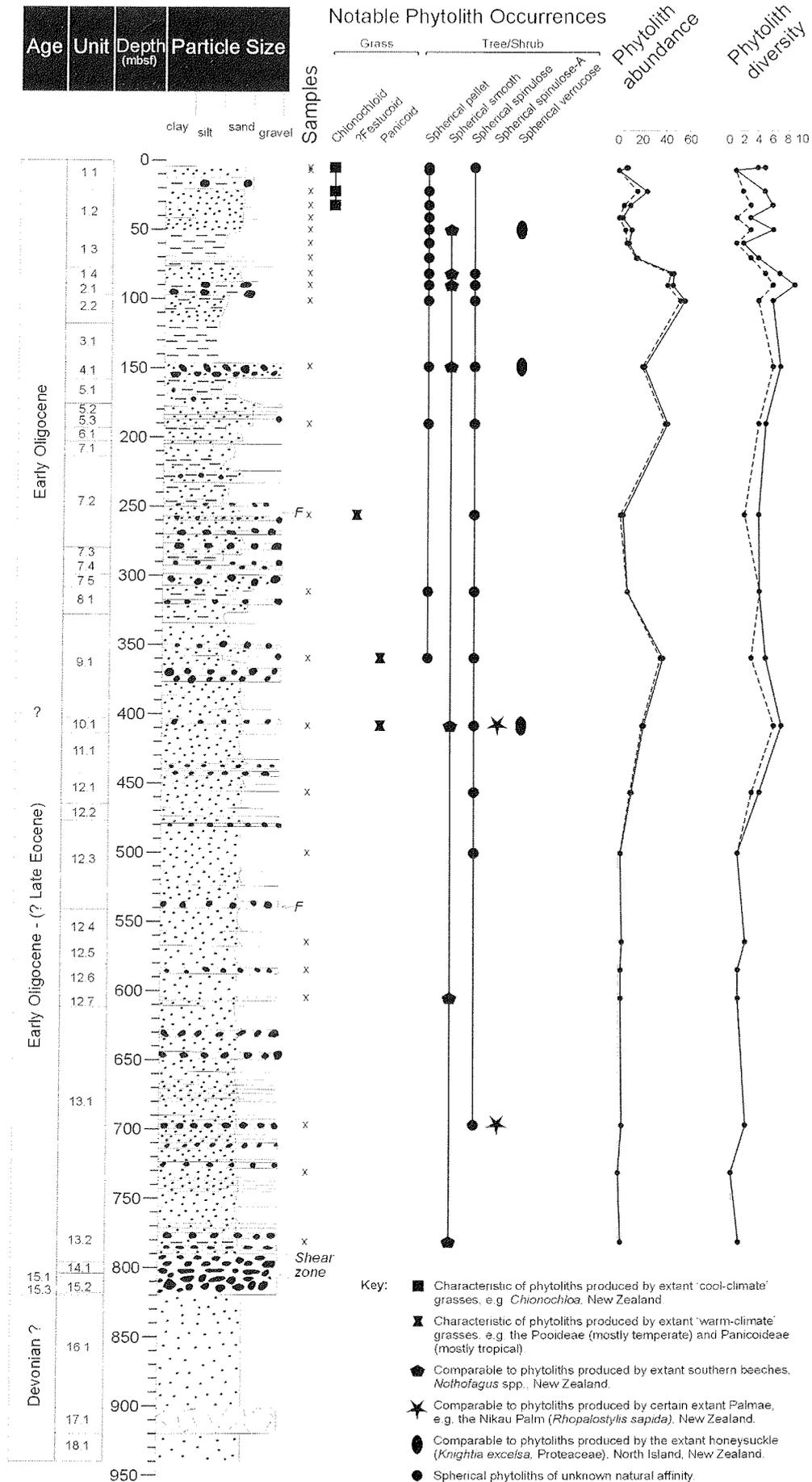


Fig. 3 - CRP-3 notable phytolith occurrences, abundance and diversity. For explanation, see figure 2.

of plant (after Kondo et al., 1994). Where possible, comparisons to modern analogues and the habitat or climatic preferences of the originating plant, and other known occurrences in the Antarctic fossil record are presented following the descriptions of each class.

PHYTOLITHS CHARACTERISTIC OF GRASSES

Phytolith morphologies characteristic of modern grasses (Gramineae) occur in low abundance in both cores, down to 436.98 mbsf in CRP-2/2A and 408.58 mbsf in CRP-3.

Fan-shape (Figs. 4a & b)

Two specimens of phytoliths originating from bulliform (motor) cells (rectangular and fan-shaped) are present in CRP-2/2A, but this form was not observed in CRP-3. The rectangular form is 58 μm long, has an approximately rectangular outline, high relief, bevelled edges, and dissolution hollows on an otherwise smooth surface. The fan-shaped form is 20 μm long, tapers to a point on one side, and has a rugulose surface. Fan-shaped phytoliths occur in modern grasses. For example, extant *Rytidosperma* of the Arundinoideae (a reed grass) is a common source of this form in New Zealand (Kondo et al., 1994). Modern reed grasses are hygrophilous and grow on moist ground. Fan-shaped phytoliths are also recorded from the early Oligocene strata cored by CIROS-1, 70 km south of Cape Roberts (Barrett, 1989, Kondo et al., 1994) (Fig. 1).

Chionochloid (Fig. 4c)

Spool-shaped short cell phytoliths are rare and only occur in the upper parts of both cores. Chionochloid phytoliths observed range from 8 to 10 μm long and have smooth margins and surfaces. Chionochloid phytoliths occur in the leaves and sheaths of extant *Chionochloa* (snow and red tussock) and *Cortaderia* (Arundinoideae) in New Zealand (Kondo et al., 1994). At the present-day *Chionochloa* grassland is mainly confined to mountains above the tree limit (Wardle, 1991) and so is interpreted as evidence of 'cool' conditions.

Elongate (Figs. 4d - f)

Elongate phytoliths of varied form and surface ornamentation are present in both cores. Abundances are low (eight specimens in CRP-2/2A and ten in CRP-3), but they are more common than other 'grass' phytolith classes. These forms are approximately rectangular rods or laths with rounded or fractured ends, ranging from 23 to 45 μm long in CRP-2/2A and 18 to 48 μm long in CRP-3. The margins are predominantly straight, but can be slightly curved or irregular. The surface textures are varied, including folded, rugulose and smooth with medium to high relief. An 'elongate' specimen with a rough surface

texture, observed at 296.19 mbsf in CRP-2/2A, is directly comparable to a specimen from 123.85 mbsf in CRP-1 (Carter, 1998a). However, after further observation both specimens are considered to be highly weathered sponge spicules. The elongate phytolith class is non-diagnostic, occurring in Gramineae, other monocotyledons, ferns and some trees (Kondo et al., 1994). Kondo et al. (1994) also noted the presence of elongate phytoliths of both grass and fern origin in CIROS-1.

?*Festucoid* (Fig. 4g)

One possible festucoid class phytolith is present at 257.10 mbsf in CRP-3. The specimen is 47 μm long and elongate-rectangular in outline. It may also be a broad elongate, but along one long edge a partially abraded crenulate margin occurs. This is characteristic of the festucoid phytolith form. The opposite long edge and three-dimensional form are obscured by the orientation of the specimen. The uppermost surface is smooth, with slight pitting at one end and in the centre of the specimen. The crenulate margin is darker in colour and has a lower relief than the central part of the specimen. Phytoliths of this class originate in the epidermal cells of Pooideae and some Arundinoideae. Most of the exotic pasture and native grasses in New Zealand, for example *Poa* and *Festuca*, produce phytolith forms of this class (Kondo et al., 1994). The Pooideae are mostly temperate in distribution (Chapman & Peat, 1992), therefore the presence of festucoid phytoliths is interpreted as evidence of relatively 'warm' conditions.

Panicoid (Fig. 4h)

Two well-preserved panicoid phytoliths of very similar form are present in CRP-3, but none occur in CRP-2/2A. The specimens are 16 and 19 μm long and approximately symmetrical with a smooth dumbbell-shaped outline. Around the edge, a narrow slightly wavy, low relief margin is evident. The surface texture is very smooth with etched areas at one end. Panicoid phytoliths originate from epidermal cells in Panicoideae, some Arundinoideae, some Eragrostoideae (Kondo et al., 1994) and some possibly cold climate Festucoideae (Diane Hart, pers. comm. 2001). Further, a very small number of modern Cyperaceae (sedge) species, for example *Epischoenus villosus*, have been recorded as producing dumb-bell-shaped phytoliths (Metcalf, 1971). In general, however, panicoid phytoliths are another characteristic form of 'warm' climate grasses (Twiss, 1992). Chapman & Peat (1992) describe the distribution of the Panicoideae as largely, but not exclusively tropical. The CRP-3 panicoid phytoliths compare very well to those extracted from a 6.5 m deep core taken at Bidwill Hill in south-eastern North Island, New Zealand (Carter & Lian, 2000) (Fig. 4i). The taxonomic significance of the latter specimens is unknown.

PHYTOLITHS CHARACTERISTIC OF TREES OR SHRUBS

Phytoliths characteristic of trees or shrubs are relatively common in both cores, occurring down to 505.03 mbsf in CRP-2/2A (below which no phytoliths were observed) and to the lowermost sample in CRP-3 at 781.26 mbsf.

Anticlinal epidermal (Fig. 4j)

Anticlinal phytoliths are found very rarely in CRP-2/2A and only one specimen was observed in CRP-3. The forms are plate-like with relatively low relief, have smooth surfaces, and range in length from 22 to 47 μm . All exhibit embayments in the margins, ranging from broad bays to tight coves, and have a distinct edge. Kondo et al. (1994) cite anticlinal epidermal phytoliths as longer when originating from ferns (77-200 μm) than dicotyledonous trees (12 to 85 μm). Therefore the CRP anticlinal epidermal phytoliths are thought to have originated from the epidermis of tree leaves.

?*Cystolith* (Fig. 4k)

Two possible cystolith specimens occur in CRP-3. Both are elliptical in outline with moderate relief, a rough rugulose surface texture, and are 18 and 34 μm long. Cystoliths are non-diagnostic and originate in epidermal cells called lithocysts (Kondo et al., 1994; Piperno, 1988).

Hair cell (Figs. 4l & m)

One non-segmented (unicellular) hair cell phytolith occurs at 50.47 mbsf in CRP-3 (Fig. 4l). The specimen is 11 μm long, has a smooth surface, and rapidly tapers to a point at the apex. Hair cell phytoliths originate from the epidermal hair of leaves and vary in size within a single leaf (Kondo et al., 1994). They are common phytoliths from dicotyledonous families, but can also be extracted from a few monocotyledons such as grasses and sedges (Piperno, 1988).

Two hair base cell phytoliths, derived from epidermal cells from which the hair cell originates, occur at 190.81 mbsf in CRP-3 (Fig. 4m). Both specimens are small (7 μm including spinules), and have a spherical outline and a central protuberance with long radiating spinules. Hair base cells are present in the epidermis and are again common in dicotyledons (Piperno, 1988).

?*Polyhedral epidermal* (Figs. 4n - p)

?Polyhedral phytoliths are relatively common in both cores and are characterised by a plate-like form, with low to high relief, and three to five approximately straight edges meeting at well-defined corners at varied angles. Outlines are approximately triangular, rectangular or polygonal, and specimens range in size from 15 to 53 μm long. The surface

textures vary, but include folded (Fig. 4n), smooth (Fig. 4o), and striated (Fig. 4p). Only phytoliths of this class with distinctive morphologies were counted, and amorphous plate-like fragments were ignored due to their lack of diagnostic utility. Therefore, the overall tally from this group (and consequently the overall phytolith total per sample) should be viewed with caution (Tab. 1). This problem requires further investigation and the definition of these phytolith forms clarified. Polyhedral epidermal phytoliths originate from leaf epidermis and are common in deciduous angiosperm trees, but have also been extracted from the monocotyledon families Commelinaceae and Gramineae (Geis, 1973; Piperno, 1988; Kondo et al., 1994). Polyhedral phytoliths have also been recorded from CRP-1 (Carter, 1998a).

Spherical

Spherical phytoliths are the most common form recovered from both cores, occurring down to 505.03 mbsf in CRP-2/2A (51% of all phytoliths counted) and 781.26 mbsf in CRP-3 (89%) (Figs. 2 & 3). The spherical forms observed are further sub-divided into ten broad non-taxonomic classes, including several forms that exhibit specific, repeatable features and have the potential to be taxonomically significant on further study. However, differences may as much be due to plant age and environmental history as plant species. Spherical phytoliths originate from the epidermal cells of leaves and also from the ray and parenchyma cells of wood.

Banded (Fig. 5a)

Specimens of this distinct form occur at 328.00 mbsf in CRP-2/2A (one specimen) and at 90.86 mbsf in CRP-3 (two specimens). This smooth spherical form, between 5 and 11 μm diameter, exhibits a characteristic raised equatorial band that covers approximately one third of the grain. The distinctiveness of this form suggests that it may be taxonomically significant on further study.

Foveolate (Figs. 5b & c)

Specimens assigned to this class occur in both cores and are circular to sub-circular in outline. Regularly arranged shallow pits, each *c.* 2 μm in diameter, occur over the entire surface. These distinctive specimens range in diameter from 10 to 17 μm and occasionally exhibit a bulbous protuberance indicating a former site of attachment in the originating plant (Fig. 5c).

Irregularly folded (Fig. 5d)

Spherical phytoliths assigned to this class occur in both cores. These forms have an irregular, but generally spherical outline with a highly folded surface texture consisting of many narrow ridges and troughs. They are commonly of high relief and range

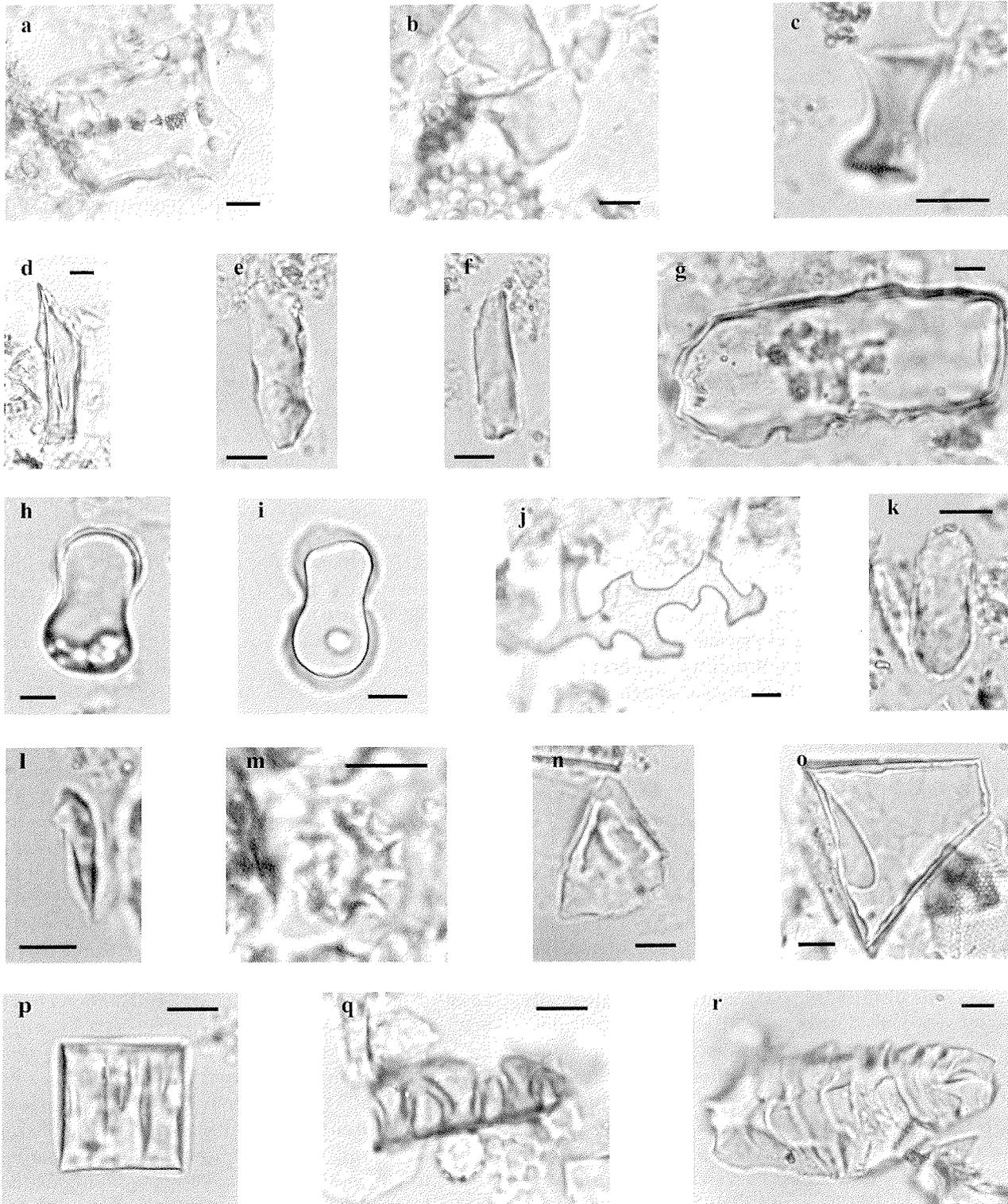


Fig. 4 - Selected phytoliths from CRP-2/2A and CRP-3 with modern analogue (Fig. i) for comparison. Scale bars 5 μ m, except (a) 10 μ m. Sample depths refer to the top of the sampled interval in metres below sea floor (mbsf). Prefix to sample depth refers to the core. Grass phytoliths: a) Fan-shaped, rectangular form, 2/2A-123.39 mbsf; b) Fan-shaped, fan form, 2/2A-436.98 mbsf; c) Chionocholoid, 3-2.85 mbsf; d) Elongate, folded form, 3-22.26 mbsf; e) Elongate, rugulose form, 3-32.20 mbsf; f) Elongate, smooth form, 3-32.20 mbsf; g) ?Festucoid, 3-257.10 mbsf; h) Panicoid, 3-359.18 mbsf; i) Panicoid, Bidwill Hill, Wairarapa, New Zealand (Carter & Lian, 2000). Tree/shrub phytoliths: j) Anticlinal epidermal, 2/2A-137.97 mbsf; k) ?Cystolith, 3-82.34 mbsf; l) Hair cell, uni-cellular hair form, 3-50.47 mbsf; m) Hair cell, hair cell base form, 3-190.81 mbsf; n) ?Polyhedral epidermal, folded form, 2/2A-27.99 mbsf; o) ?Polyhedral epidermal, smooth form, 2/2A-250.99 mbsf; p) ?Polyhedral epidermal, striated form, 3-149.98 mbsf; q) Tracheid with spiral thickening (and spherical-spinulose phytolith), 3-90.86 mbsf; r) Tissue, 2/2A-52.99 mbsf.

in diameter from 9 to 16 μm . Spherical irregularly folded phytoliths are produced by certain monocotyledon families (Marantaceae, Cannaceae, Zingiberaceae) of the Zingiberales (aromatic herbs) (Piperno, 1988). Spherical phytoliths of this form are similar to specimens extracted from an undescribed Ross Sea core (Carter, pers. comm.).

Multifaceted (Figs. 5e & f)

Phytolith forms assigned to this class are distinctive and occur in both cores. The surface texture consists of numerous adjoining folded (Fig. 5e) or smooth (Fig. 5f) facets, ranging from 8 to 24 μm in diameter. Spherical multifaceted phytoliths have been extracted from CRP-1 (Carter, 1998a), an undescribed Ross Sea core (Carter, pers. comm.) and a Sirius Group core at Mt. Feather, Antarctica (Carter, 1998b).

Pellet (Fig. 5g)

This previously undescribed class encompasses the most common phytolith form extracted from CRP-2/2A and the upper c. 360 m of CRP-3. Spherical pellet forms are a darker shade than the other phytoliths recovered, presumably because they contain higher quantities of occluded carbon, and are generally small, ranging in diameter from 6 to 13 μm . Their outline is predominantly spherical, but commonly irregular, with an angular margin.

Rugulose (Figs. 5h & i)

Phytoliths assigned to this class occur in both cores, but more commonly in CRP-3. These spherical forms have high relief and a rugged surface texture of low bulges and hollows, and range from 6 to 13 μm in diameter. Five specimens of a distinct form (spherical rugulose-A) ranging from 7 to 15 μm in diameter occur at 82.34 mbsf in CRP-3 (Fig. 5i). These forms have an irregular surface texture but exhibit lower relief than the other specimens in this class. This distinct form is potentially taxonomically significant with further study. The spherical rugulose forms are distinguished from the spherical spinulose forms by a lower and smoother surface texture. Piperno (1988) notes that there is a distinct size difference between spherical rugulose phytoliths extracted from monocotyledons (9–25 μm) and dicotyledons (3–9 μm). The size ranges of those observed in CRP-2/2A and CRP-3 suggest that both groups may be represented in the assemblage.

Smooth (Fig. 5j)

Rare spherical smooth phytoliths occur in both cores. These forms have a regular circular outline, a smooth surface and range in diameter from 8 to 10 μm . These forms compare well to phytoliths extracted from extant *Nothofagus solandri* var. *cliffortioides* (New Zealand's mountain beech; Fig. 5k) which grows in the drier areas of montane

and subalpine habitats. Similar forms are produced by other *Nothofagus* species (Kondo et al., 1994). Piperno (1988) noted that significant numbers of smooth sphericals between 1 and 50 μm in diameter are produced by deciduous angiosperms. Smooth sphericals with occasional narrow surface ridges and etching were extracted from CRP-1 and compared to extant *Nothofagus menziesii* (silver beech), also from New Zealand (Carter, 1998a). Kondo et al. (1994) also extracted spherical smooth phytoliths from the CIROS-1 core and extant members of the Cunoniaceae, Lauraceae and Myrtaceae families, as well as *Cyathea medullaris* (black tree fern) and *Empodisma minus* (wire rush) from New Zealand.

Spinulose (Figs. 5l & m)

Spherical spinulose phytoliths are the second most abundant form observed throughout the CRP-3 core. Only one specimen occurs in CRP-2/2A, at 250.99 mbsf. Spherical spinulose phytoliths originate from stegmata cells in leaves, which have unevenly thickened walls. The majority of the specimens observed have a spherical form with a surface texture characterised by varying densities of low spinules with either rounded or pointed apices (Fig. 5l), and range between 6 and 14 μm in diameter. Three specimens of a distinct highly spinulose form (spherical spinulose-A) occur at 408.58 mbsf (two specimens) and 697.35 mbsf in CRP-3 (Fig. 5m). This form exhibits a spherical to elliptical outline and is densely covered in regular, well-defined spinules with predominantly pointed apices. The maximum diameters of the three specimens observed are 8, 10 and 12 μm , including spinules up to 1 μm in length. This form is directly comparable to phytoliths extracted from certain Palmae, for example, the nikau palm of New Zealand (*Rhopalostylis sapida*; Fig. 5n). This species grows where water is permanently available throughout the slightly milder North Island and thrives in coastal broadleaf forest on the west coast of the upper South Island. Similar forms have been extracted from mesophyll leaf cells of other Palmae (Piperno, 1988) and *Ceroxylon parafrons* syn. *utile* – a montane palm from Ecuador that grows between 2500 and 3500 m altitude (Fig. 5o). Spherical spinulose phytoliths have also been extracted from Bromeliaceae (monocotyledon herbs) (refer to Discussion), but have been distinguished from Palmae phytoliths by their size – the former range between <2 and 8 μm and the latter between 6 and 25 μm (Piperno, 1988). Spherical spinulose phytoliths of palm origin in subtropical and tropical soils described by Kondo (1977) ranged from 5–30 μm , however Kondo et al. (1994) state that New Zealand nikau palm phytoliths of this form are mostly < 10 μm in diameter. Further work needs to be completed on both groups in order to be able to confidently distinguish these forms on the basis of size.

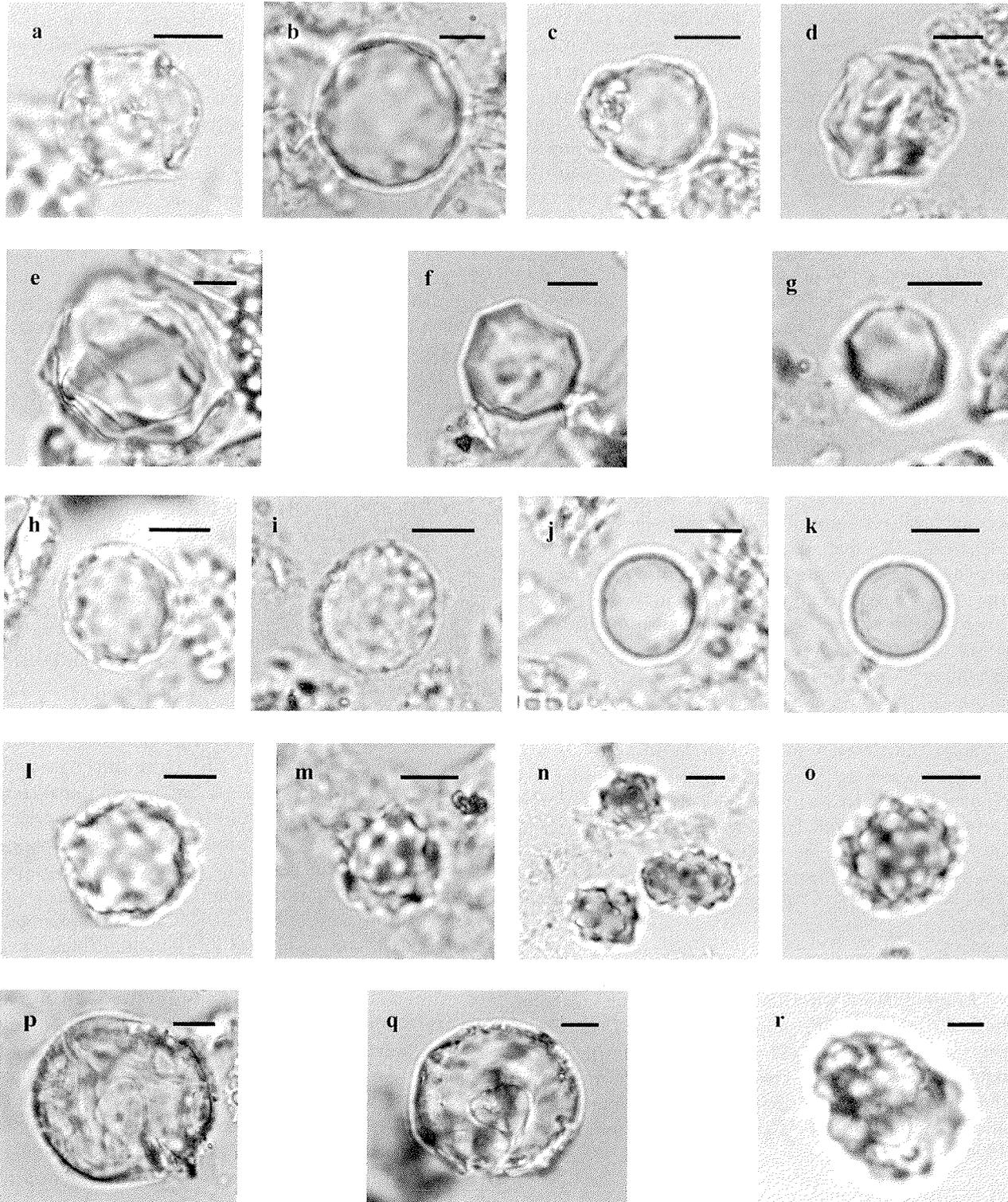


Fig. 5 - Selected spherical (tree/shrub) phytoliths from CRP-2/2A and CRP-3 with modern analogues (Figs. k, n, o & q) for comparison. Scale bars 5 μ m. Sample depths refer to the top of the sampled interval in metres below sea floor (mbsf). Prefix to sample depth refers to the core. a) banded, 3-90.86 mbsf; b) foveolate, 2/2A-123.39 mbsf; c) foveolate with attachment protuberance, 3-90.86 mbsf; d) irregularly folded, 2/2A-296.19 mbsf; e) multifaceted, folded form, 2/2A-27.99 mbsf; f) multifaceted, smooth form, 2/2A-505.03 mbsf; g) pellet, 2/2A-505.03 mbsf; h) rugulose, 3-90.86 mbsf; i) rugulose-A, 3-82.34 mbsf; j) smooth, 3-50.47 mbsf; k) modern *Nothofagus solandri* var. *cliffortioides* phytolith, New Zealand; l) spinulose, 3-457.39 mbsf; m) spinulose-A, 3-408.58 mbsf; n) modern nikau palm phytoliths, *Rhopalostylis sapida*, New Zealand; o) modern *Ceroxylon parafrons* syn. *utile* phytolith, Ecuador; p) striated, 2/2A-27.99 mbsf; q) modern *Libocedrus bidwillii* phytolith, New Zealand; r) verrucose, 3-408.58 mbsf.

Striated (Fig. 5p)

Two specimens assigned to this class occur at 27.99 mbsf in CRP-2/2A. Both are large (25 and 30 μm in diameter) with circular to sub-circular outlines and moderate relief. This form is characterised by fine linear surface striations, randomly oriented, on an otherwise smooth surface; and a distinct sub-circular indentation representing an attachment scar. These spherical striated phytoliths directly compare with phytoliths extracted from the extant New Zealand, kaikawaka (*Libocedrus bidwillii*; Fig. 5q) which grows in montane and subalpine habitats throughout the country. The presence of this form is interpreted as evidence of 'cool' conditions.

Verrucose (Fig. 5r)

Spherical verrucose phytoliths occur rarely in CRP-3. These distinct spherical to sub-spherical forms range in diameter between 7 and 17 μm and are characterised by a surface texture of dense, globular nodules of varying sizes. The distinctiveness of this form suggests that it has the potential to be taxonomically significant with further study. Kondo et al. (1994) state that spherical verrucose phytoliths are produced by *Nothofagus* spp. (except *N. menziesii*), the New Zealand honeysuckle, rewarewa (*Knightia excelsa*, Proteaceae), and are also similar to those extracted from *Empodisma minus* (wire rush). Scanning electron microscope photographs in Kondo et al. (1994) suggest that the varied sizes of the verrucae and the globular nature of the CRP forms compare most closely to those produced by rewarewa. The Proteaceae are mainly distributed in Australia and South Africa. In New Zealand, rewarewa occurs throughout the North Island to northern South Island in lowland or montane habitats. Spherical verrucose phytoliths tentatively attributed to *Nothofagus* were extracted from the CIROS-1 core by Kondo et al. (1994).

Tracheid (Fig. 4q)

Fragments of silicified tracheid occur rarely in both cores and are non-diagnostic. Figure 4q illustrates an example (21 μm long) exhibiting spiral thickening (a small spherical spinulose form is also in the photograph). Silicified tracheid fragments were also recorded from the CIROS-1 core (Kondo et al., 1994).

Tissue (Fig. 4r)

Fragments of silicified epidermal tissue (up to 44 μm long) occur only at 52.99 and 79.99 mbsf in CRP-2/2A. These tissue fragments could not be determined taxonomically.

DISCUSSION

The terrestrial palynomorph assemblages from both cores contain an element of re-worked older Cenozoic and Permian-Mesozoic grains. In the

phytolith assemblage, re-worked grains may only be recognised by the state of preservation. Phytoliths throughout both cores are well-preserved; delicate plate-like, anticlinal (Fig. 4j) and ornamented spherical (Fig. 5m) forms indicate the effects of dissolution are minimal. Occasional specimens exhibit dissolution hollows and impact notches, the latter presumably attained during transport to the site of deposition. Therefore, it is assumed that good preservation throughout both cores and the lack of Beacon Supergroup phytoliths as recognised by Carter (1999) suggests minimal phytolith re-working. The effect of dissolution on phytolith abundance with increasing burial depth in the cores is unknown. However, both overall abundance and diversity decrease in samples below approximately 400 mbsf in each core (Figs. 2 & 3), with only the more robust spherical forms preserved below approximately 450 mbsf in each core.

CRP-2/2A - EARLY OLIGOCENE-EARLY MIOCENE ASSEMBLAGE (29-19 Ma)

The phytolith record of CRP-2/2A is sparse, with relatively low abundance and form diversity throughout (Fig. 2). The maximum number of 68 phytoliths in one sample occurs at 27.99 mbsf, with the highest total diversity evident in the upper c. 124 m of the core. Spherical class diversity is also relatively high in the upper part of the core, reaching six forms at 27.99 mbsf. The irregularly folded, multifaceted, pellet, rugulose and smooth spherical classes are present throughout the core. Grass phytoliths (fan-shape, chionochloid and elongate classes) do not occur below 436.98 mbsf. Notable occurrences in the assemblage include the chionochloid and spherical striated specimens at 27.99 mbsf, the persistent and abundant spherical pellet class and the single spherical spinulose specimen at 250.99 mbsf. Below c. 250 mbsf, diversity and abundance are very low and follow similar trends, suggesting that the low counts do not adequately reflect the source vegetation.

The very high proportion of tree/shrub (51% spherical, 45% other) to grass (4%) phytolith classes is interpreted as signifying derivation from a woody (woodland or scrub) source vegetation community. Trees and shrubs are known to produce far less phytolith material than grasses. For example, *Nothofagus* spp. have been found to produce 2.5 times less phytolith material than *Chionochloa* spp. (Carter & Lian, 2000). Therefore, a dominance of spherical forms in a phytolith assemblage implies an abundance of trees or shrubs at the site of phytolith entrainment. The diversity of the spherical forms implies a relatively diverse woody community, although as noted previously, different forms may not necessarily reflect different species.

The terrestrial palynomorph record for CRP-2/2A also suffered from low grain counts. This was interpreted as being due to a combination of sparse source vegetation, rapid sediment accumulation causing dilution of the biogenic grains (the average sediment accumulation rate is estimated at 100 m/m.y.), and possible winnowing of the fine-grained sediment (CRST, 2000). It is highly probable that these factors would also have affected the phytolith assemblage. The terrestrial palynomorphs exhibit a slight increase in diversity and abundance below *c.* 307 mbsf, which is more marked below 443 mbsf (Askin & Raine, 2000). This is interpreted as a climatic threshold (dated at *c.* 24 Ma) from a milder Early Oligocene cold temperate-periglacial climate to a sub-polar climate evident in the upper part of the core (CRST, 1999). The terrestrial palynomorphs suggest the vegetation above *c.* 307 mbsf consisted of a herb-moss tundra with a few prostrate (ground-hugging) woody plants (for example, *Nothofagus lachlaniae* and *Podocarpidites* spp.) in protected areas. This interpretation mirrors that modelled for the Miocene in CRP-1. Below this level, the terrestrial palynomorphs suggest a low-diversity, woody vegetation (including several species of *Nothofagus* and podocarps) predominated in slightly milder conditions. The phytolith assemblage also shows a slight increase in diversity and abundance below *c.* 362 mbsf, but decreases again below *c.* 437 mbsf, perhaps due to burial dissolution. Whether this trend is climatically significant is unknown because interpretation is hindered by low counts. A comparison of taxonomic composition between the phytolith and terrestrial palynomorph assemblages is difficult due to restricted knowledge of modern analogues. In addition, mosses do not produce phytoliths and gymnosperms only rarely (Kondo et al., 1994), so we would only expect the latter component to be present in small quantities in the phytolith assemblage. However, the smooth (and possibly verrucose) spherical forms may represent the *Nothofagus* component of the palynoflora.

In summary, the tentative interpretations from the phytolith assemblage of CRP-2/2A suggest a predominantly woody vegetation in the hinterland with local areas of grass in more exposed locations throughout deposition. The occurrence of phytoliths comparable to montane/subalpine *Libocedrus* and tussock grasses suggests there may have been a cool climate regime, just mild enough to sustain hardy woodland or scrub, at least during deposition of the top of the core. Despite the low counts, the phytoliths support the terrestrial palynomorph interpretations for the source vegetation during the deposition of CRP-2/2A. Both assemblages indicate a prominent woody component to the vegetation including evidence of *Nothofagus*, whereas the podocarps are only present in the palynoflora and *Libocedrus* only in the

phytolith assemblage. The rare occurrence of grass phytoliths in the upper *c.* 437 m may be an additional component of the herb-moss tundra vegetation not represented in the palynoflora. There is no direct evidence in the phytolith assemblage for a climatic threshold at *c.* 24 Ma as indicated by the palynoflora. However, the rare montane/subalpine *Libocedrus* and tussock grass phytoliths occurring at 27.99 mbsf are possibly comparable to the sub-polar climate interpreted from the palynoflora for this upper core interval.

CRP-3 - EARLY OLIGOCENE ASSEMBLAGE (*c.* 34-31 Ma)

The phytolith assemblage of CRP-3 is also sparse with relatively low abundances and form diversity throughout (Fig. 3). The maximum count of 55 phytoliths occurs at 101.03 mbsf with the highest diversity in the top *c.* 100 m of the core. Spherical class diversity fluctuates, but peaks with six distinct classes at 90.86, 149.98 and 408.58 mbsf. The smooth and spinulose sphericals are the most persistent forms throughout the core. Notable occurrences within the spherical classes include the occurrence of pellet forms only within the upper *c.* 360 m, abundant spinulose forms throughout the core, very rare spinulose-A at 408.58 mbsf and 697.35 mbsf, and verrucose forms between 50.47 mbsf and 408.58 mbsf. Sparse grass phytoliths occur down to 408.58 mbsf, with rare chionochloid/elongate forms occurring at and above this level, and single occurrences of ?festucoid/panicoid forms occurring below 257.10 mbsf. Below *c.* 50 mbsf, form diversity approximately mirrors abundance implying that the counts are not high enough to adequately reflect the source vegetation.

The very high proportion of tree/shrub (96%) to grass (4%) phytoliths suggests predominantly woody vegetation in the source area. Rare grasses below 257.10 mbsf that preferred milder conditions were replaced above 32.20 mbsf by local patches of tussock grass growing in more upland or exposed locations. No Gramineae phytoliths occur below 408.58 mbsf, suggesting perhaps closed canopy woody vegetation. Below *c.* 250 mbsf (perhaps up to *c.* 50 mbsf), patches of ?Proteaceae and 'warm climate' grasses or possibly sedges may have grown on favourable sites, for example north-facing mid-slopes or along the coast. The occurrence of the spherical pellet form throughout CRP-2/2A and the upper *c.* 360 m of CRP-3 may be related to the growth of a woody plant that preferred cooler growing conditions than those prevalent during the lower part of CRP-3. Conversely, the prominence of spherical spinulose forms in CRP-3 and the single specimen occurrence in CRP-2/2A suggests the

occurrence of a woody plant preferring slightly warmer growing conditions.

The spherical spinulose-A phytoliths have been tentatively compared to those produced by modern *Palmae* and distinguished from similar *Bromeliaceae* phytoliths on the basis of size. The modern geographic range of these families is similar, with the *Bromeliaceae* centred in tropical and warm temperate America and the palms being more widespread, but chiefly tropical (with some subtropical and a few temperate outliers) (Heywood, 1978). Both groups prefer generally 'warm' growing conditions, but they differ in their humidity preferences with the *Bromeliaceae* being adapted to xerophytic and the *Palmae* to moist growing conditions. Evidence from the CRP-3 terrestrial palynomorph record suggests the growing conditions at the Southern Victoria Land coast during the period of deposition were unlikely to be very dry, with particularly *Coptospora* (moss, CRP-2/2A & CRP-3) and ?*Cyperaceae* (sedge, CRP-3) species present within a predominantly woody vegetation assemblage. Therefore it is suggested that despite the rarity of spherical spinulose-A phytoliths observed in CRP-3, for the section below *c.* 408 mbsf vegetation associations were possibly supplemented by *Palmae*, implying that temperatures were slightly warmer than implied higher in the core, and water was permanently available. It appears more likely that the distribution of *Palmae* is related to humidity rather than high temperatures. Humid climatic regions not only include the high temperature tropical rainforests (no winter, coolest month >18°C), but also the 'warm humid' (mild winters, coolest month 0–18°C, warmest month >10°C) and 'cool humid' zones (severe winter, coldest month <0°C, warmest month >10°C) (Bartholomew et al., 1980). For example, the Ecuadorian palm *Ceroxylon parafrons* grows at altitude, surviving low temperatures, but requiring the moist conditions of the Tropics.

The occurrence of *Palmae* phytoliths in an assemblage representing vegetation growing in a cold temperate regime, where we know from sedimentological evidence that glaciers were calving at sea-level (CRST, 2000), may seem incongruous. It is assumed that contamination of the samples by extant *Palmae* did not occur because monocotyledons are known to produce large quantities of phytoliths (Piperno, 1988) so we would have expected much higher quantities in more than the two samples, which came from different processing batches. Further, a windblown source for the phytolith assemblage as a whole is unlikely with reference to the palaeogeography, modern polar wind patterns and the onshore fossil record. Phytoliths (and diatoms) have been shown to travel >2000 km from their source in the Sahara and Sahel regions of Africa across the North Atlantic (for example, Folger, 1970; Folger et al., 1967; Romero et al., 1999). The most recent

palaeogeographical reconstruction of the south polar region during the Late Eocene (40 Ma) indicates that Tasmania and the south Australian coast are within this distance from the relative location of Cape Roberts in Southern Victoria Land (Lawver et al., in prep.). However, modern wind patterns in the south polar region tend to be circumpolar or southerly with only the upper Troposphere and Stratosphere winds blowing towards the Pole. Therefore, for windblown phytoliths to reach Cape Roberts, they would first have to enter high atmospheric levels. Further, evidence from the Middle-Late Eocene Southern McMurdo Sound erratics of leaves, wood and pollen (Stilwell & Feldmann, 2000), plus the Early Oligocene *Nothofagus* sp. leaf discovered at 46 mbsf in CRP-3 imply a significant non-windblown local/regional woody vegetation and a more likely source for the phytolith flora.

The apparent mixture of phytoliths characteristic of plants from 'tropical' and 'cool' climatic regimes has also been noted in the palynoflora of the New Zealand Cenozoic (Mildenhall, 1980). Here, the presence of 'tropical' pollen is also interpreted as reflecting high humidity rather than very high temperatures (although these were still 'warm'). This interpretation helps one envisage the occurrence of palms in favourable locations near Cape Roberts during the Early Oligocene.

Overall, the sparse phytolith assemblage supports the terrestrial palynomorph interpretations of the source vegetation during the deposition of CRP-3. Both assemblages indicate a prominent woody component to the vegetation, similar to the CRP-2/2A assemblages. Smooth spherical phytoliths throughout the core are consistent with the presence of *Nothofagus* spp., which are also a common element of the palynoflora, but the presence of Gramineae, and possible *Palmae* and *Proteaceae* are only recorded in the phytolith assemblage. High counts of terrestrial palynomorphs at 114.90 mbsf (224 specimens) and 190.77 mbsf (416) in CRP-3 are paralleled by relatively high phytolith counts at similar levels of 101.03 m (55) and 190.81 m (41). This could be due to several factors, including dense source vegetation (overall or just a local patch), a slower sedimentation rate causing slight concentration of microfossils or increased proportions of re-worked specimens at these levels. The taxonomic composition of the palynoflora is similar to that of the lower part of CRP-2/2A, suggesting low diversity woody vegetation with several species of *Nothofagus*, podocarps and mosses. The pockets of low scrub or closed forest in favourable sites interpreted from the palynoflora may reflect the pockets of *Palmae*, ?*Proteaceae* and 'warm' climate grasses interpreted tentatively from the phytolith assemblage and not present in the terrestrial palynomorph record. Further, species diversity in the palynoflora increases at 781.36 mbsf in CRP-3 and a

first occurrence of *Myricipites harrisii* (Casuarinaceae pollen), characteristic and abundant of the Eocene in New Zealand and Australia, does not rule out the possibility of the base of CRP-3 extending into the Late Eocene (CRST, 2000).

CONCLUSIONS

In summary, despite a paucity of data, the phytolith assemblages suggest a very gradual decrease in temperature upward through the two cores. The mildest temperatures are tentatively interpreted for the CRP-3 section below *c.* 250 mbsf, with the rare occurrence of Palmae, ?Proteaceae and 'warm' climate grasses, and the coolest for the top of CRP-2/2A, with the similarly rare occurrence of tussock grass and montane *Libocedrus*. The phytoliths (and terrestrial palynomorphs at 781.36 mbsf) imply localised mild conditions during deposition of the lower part of CRP-3, and may represent remnants of the moist, temperate vegetation interpreted from Middle to Late Eocene fossil wood, leaves and pollen assemblages in the Southern McMurdo Sound erratics (Stilwell & Feldmann, 2000).

The majority of phytolith forms observed from CRP-1 (Carter, 1998a) were also recorded from CRP-2/2A and CRP-3. However, Carter (1998a) recorded an abundance of irregular multifaceted forms (comparable with extant Magnoliales forms) and irregular cubic forms not recorded in this study. The tentative phytolith analysis from all three cores is compatible with the interpretations from the terrestrial palynology and has provided additional information about the vegetation composition. Extrapolating preferred growing conditions from comparable modern analogues also provides independent climatic interpretations, allowing broad indications of temperature and humidity conditions throughout deposition.

Terrestrial palynomorph results from the CIROS-1 core, which covers a similar time interval from the Late Eocene to Early Miocene (Hannah et al., 1997; Wilson et al., 1998), suggest full forest conditions along the Antarctic coastline with a humid oceanic climate of limited temperature range (Mildenhall, 1989). The variety of *Nothofagus* and other angiosperm pollen, including proteas, is variably interpreted as representing a climate that was "at times cool temperate or temperate" (Mildenhall, 1989, abstract) or "temperate, if not at times warm temperate" (Mildenhall, 1989, text). It is likely that the latter mild conditions may have occurred in local pockets, similar to the palaeoenvironment interpreted from the lower CRP-3 phytoliths and terrestrial palynomorphs. Overall, however, the CRP-2/2A and CRP-3 phytolith and terrestrial palynomorph analyses suggest similar cool regional conditions to the CIROS-1 palynoflora interpretation for this interval.

The application of phytolith analysis to future Antarctic Cenozoic projects would greatly benefit from the study of modern analogues from extant plants on the Antarctic Peninsula and sub-Antarctic Islands as without a comprehensive reference collection and terrestrial palynomorph support, interpretations from the phytolith record can only be extremely tentative.

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