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Quantitative Analysis of the Calcareous Nannofossil Assemblages from CIROS-1, Victoria Land Basin, Antarctica

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Abstract The lower portion of the CIROS-1 core (McMurdo Sound, Antarctica) has been cited as evidence for Late Eocene continental glaciation on Antarctica. A reassessment of this age determination is warranted in the face of mounting evidence from multiple proxies that continental glaciation was initiated by rapid ice-growth during the earliest Oligocene. Examination of calcareous nannofossil assemblages from this section confirmed very low fossil abundance, low species richness, and the presence of reworked taxa. A minimum of 37% of the total species richness in the section comprises reworked forms, including Late Cretaceous and latest Paleocene to Middle Eocene species. Quantitative analysis suggests a further 20-33% of the species were part of the reworked component. Given the very low abundance, sporadic occurrence, and predominance of demonstrably reworked species in the CIROS-1 section, coupled with the well-documented reworking in nearby Cape Robert Project Oligocene strata, the biostratigraphic integrity of the remaining species is clearly suspect. At best, a latest Eocene to Early Oligocene age assignment is justified. The large uncertainty in the age determination indicates that the CIROS-1 section cannot be used as evidence of a pre-Oligocene initiation of Antarctic continental glaciation.

Keywords Antarctica, calcareous nannofossils, CIROS-1, Oligocene

1. Introduction

Arguably, the most significant palaeoclimatological event of the Cenozoic was the initiation of large-scale glaciation on Antarctica. The change from greenhouse conditions of the Cretaceous and Early Palaeogene to the icehouse conditions of the later Palaeogene and Neogene affected almost every system on the surface of the Earth. High-resolution proxy records, such as those from Ocean Drilling Program (ODP) Leg 199 in the equatorial Pacific, suggest that the onset of continent-scale Antarctic glaciation occurred as a relatively rapid and stepwise set of events that occupied perhaps only 200 000 years in the Early Oligocene (Coxall *et al.*, 2005). Current thinking suggests that the timing of this event was controlled by long-term drawdown of atmospheric carbon dioxide, coupled with an astronomical trigger, in which simultaneous low eccentricity and low-amplitude change in obliquity favoured reduced seasonality, featuring the prolonged absence of warm summers (Coxall *et al.*, 2005). Climate modelling results suggest that the carbon dioxide drawdown led first to highly dynamic, high-altitude glaciers, followed by rapid coalescence and growth into continental-scale ice-sheets, as mass-balance feedbacks increased (DeConto & Pollard, 2003). This modelling yields results that are fully consistent with proxy records from the deep sea.
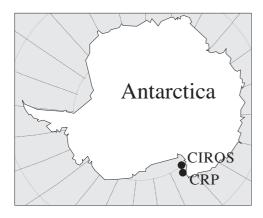
Modelling results predict that significant glaciomarine deposition should not have occurred until the growth of continent-scale ice-sheets (DeConto & Pollard, 2003). The growth of a continental ice-sheet would necessitate a large ice volume that would sequester a sufficient amount of light oxygen isotopes to result in a strong positive shift in the isotopic ratios of oceanic reservoirs. This shift is not evident until after the Eocene/Oligocene boundary in the

deep sea (Coxall *et al.*, 2005). Therefore, any evidence of significant glaciomarine deposition adjacent to the continental margin of Antarctica prior to the Oligocene would cast strong doubts on the oceanic proxy records.

Two lines of evidence have been advanced to suggest significant glaciation at sea-level on Antarctica prior to the Oligocene: ice-rafted debris (IRD) in oceanic cores and glaciomarine deposits in CIROS-1. Although several Southern Ocean Deep Sea Drilling Project (DSDP) and ODP sites have been used as evidence of pre-Oligocene IRD, none of these purported occurrences has held up under close scrutiny (Anderson, 1999). The remaining purported evidence for significant coastal glaciation on Antarctica is the record of the CIROS-1 core from McMurdo Sound, Antarctica. The Eocene age of the glaciomarine sedimentary rock in CIROS-1 was determined largely by calcareous nannofossil biostratigraphy. Given the new information on the timing of the initiation of continental glaciation on Antarctica that has emerged during the last decade, it is fitting to re-examine the biostratigraphic evidence for this now anomalous age assignment.

2. Previous work on the nannofossils from CIROS-1

The CIROS-1 corehole lies just offshore of the Transantarctic Mountains in the Ross Sea Graben (Figure 1). It is proximal to the outlet of the Ferrar Glacier, which drains a substantial portion of the East Antarctic Ice-Sheet. The corehole penetrated to a total depth of 702m below sea-floor (mbsf). It has been divided into two portions, based on gross lithologic character and stratigraphy. The upper portion (0-366mbsf) consists of massive- to weakly-bedded diamictites, interpreted as lodgment and

Figure 1: Map illustrating locations of the CIROS and Cape Roberts Project (CRP) drillholes in the Victoria Land Basin, McMurdo Sound, Antarctica
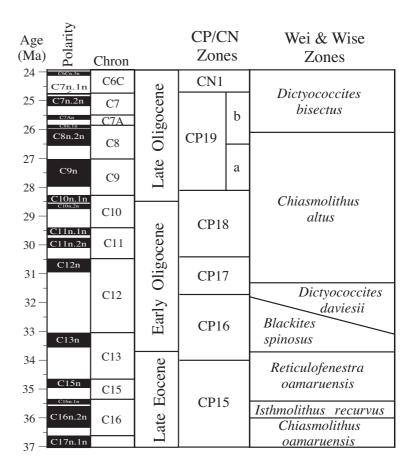
waterlain tills (Hambrey *et al.*, 1989). The upper portion has been dated as Late Oligocene to Early Miocene, based largely on diatom biostratigraphy (Harwood *et al.*, 1989). The lower portion (366-702mbsf) is dominated by mudstones and sandstones with outsize clasts and isolated diamictites, interpreted as glaciomarine deposition (Hambrey *et al.*, 1989). The age of this lower portion has been controversial, as is described below.

Edwards & Waghorn (1989) reported on their investigations of 35 samples examined for nannofossils from the CIROS-1 core. There were nannofossils in 16 samples from the lower part of the CIROS-1 core (below 385mbsf). Nannofossils are very rare and moderately to poorly preserved from these samples, which were taken preferentially from internal sediment in molluscan fossils and from fine-grained lithologies. The interval from 385.8 to 690.4mbsf was ascribed broadly to a Middle Eocene to Early Oligocene age. The presence of *Chiasmolithus altus* in the upper two samples (385.8 and 389.5mbsf) was used to place these samples in the uppermost Eocene to mid-Oligocene (Subzones CP15b to CP19a of Okada & Bukry, 1980). *Isthmolithus recurvus* was observed in the next lower sample (416.8mbsf), which Edwards & Waghorn (1989) assigned to the uppermost Eocene to lowermost Oligocene (Subzones CP15b to CP16c of Okada & Bukry, 1980). The remainder of the underlying section (450.7 to 690.4mbsf) was placed in the upper Middle Eocene to lowermost Oligocene (CP14 to CP16 of Okada & Bukry, 1980), based on the presence of *Cyclicargolithus floridanus* and relatively long-ranging taxa, such as *Reticulofenestra bisecta* and *Reticulofenestra scrippsae*.

Wei (1992) examined 31 samples from

380 to 699mbsf in the CIROS-1 core, with a sampling frequency of approximately one sample per 10m. Wei (1992) placed the upper portion of his sampled section (380 to 389.5mbsf) in the *C. altus* Zone (mid-Oligocene of Wei & Wise, 1990), based on the presence of the nominate taxon and the absence of *Reticulofenestra umbilica*. This is equivalent to the upper portion of CP17 through the lower portion of CP19 (Figure 2). A sample from 391.9mbsf was placed in the *Reticulofenestra daviesii* Zone (upper Lower Oligocene of Wei & Wise, 1990), based on the co-occurrence of *C. altus*, *Reticulofenestra hilliae* and *R. umbilica*, and the absence of *I. recurvus*, in that sample. The majority of the sampled sequence (406 to 681.2mbsf) was placed in the combined *I. recurvus-Reticulofenestra oamaruensis-Blackites spinosus* Zones (Upper Eocene to lowermost Oligocene), based on the presence of *I. recurvus* in four samples from 406 to 421mbsf, and from a single sample at 681.16mbsf.

There is a striking anomaly evident in the Wei (1992) dataset. While both *R. umbilica* and *R. hilliae* occur as rare specimens in Sample 391.9mbsf, neither occur in the relatively diverse assemblages with *I. recurvus* in samples from 406 to 420.3mbsf. This is unusual, as these reticulofenestrids have stratigraphic ranges that completely

Figure 2: Calcareous nannofossil biostratigraphic zonation for the Upper Palaeogene of the Antarctic region (after Wei & Wise, 1992), correlated with the temperate zonation (CP/CN) of Okada & Bukry (1980) and the magnetic polarity time-scale of Berggren *et al.* (1995)

encompass that of *I. recurvus*. *R. hilliae* does co-occur with *I. recurvus* in a single sample from 681.16mbsf.

Wei (1992) discussed at length the possibility that the CIROS-1 assemblages could be reworked. He concluded that the assemblages are similar in composition to presumed coeval assemblages from ODP Legs 113 and 119, suggesting biogeographic uniformity, and that the biostratigraphic succession from CIROS-1 is consistent with other Southern Ocean sites. In addition, Wei (1992) stated that no specimens of Lower Palaeogene or Mesozoic nannofossils were observed, indicating that the species present are all consistent in age. Wei (1992) discounted the possibility of reworking, based on these considerations.

Monechi & Reale (1997) examined approximately 115 samples from the lower part (367 to 697mbsf) of the CIROS-1 core, of which 59 contained nannofossils. The assemblages all contained very low abundances and diversities of nannofossils exhibiting poor preservation. Unlike the previous studies, they recognised and documented several instances of obvious reworking within the CIROS-1 lower section. Six samples (382.97, 451.64, 454.31, 490.28, 502.77 and 594.04mbsf) contain species restricted biostratigraphically to the Paleocene to early Middle Eocene. Two samples (504.49 and 556.24mbsf) contain species that can be no younger than the Late Cretaceous. Monechi & Reale (1997) combined their dataset with those of Edwards & Waghorn (1989) & Wei (1992) to reassess the biostratigraphic succession in CIROS-1 using all available nannofossil data. This expanded dataset was used to subdivide the lower portion of CIROS-1 into five biostratigraphic zones, using the zonation of Wei & Wise (1990).

The interval from 380 to 390.9mbsf was assigned to the Early Oligocene *C. altus* Zone, based on the co-occurrence of *C. altus* and *Chiasmolithus oamaruensis*. The occurrence of *R. umbilica* in Sample 382.97 was considered to be reworked, based on its occurrence with a rosette-shaped discoaster (*Discoaster* sp. of Monechi & Reale 1997, pl.3, figs 10, 11) similar in form to *Discoaster saipanensis*, and its occurrence above samples containing *C. altus*. Samples from 391.85 to 406.15mbsf were assigned to the *R. daviesii* Zone, based apparently on their lack of either *C. altus* or *I. recurvus*. The interval from 406.57 to 464.90mbsf contains *I. recurvus* (at least in its upper 15m), and occurs above the highest stratigraphic occurrence of the zonal fossil *R. oamaruensis*, indicating the *B. spinosus* Zone of Early Oligocene age. *R. oamaruensis* occurs sporadically within the interval from 467.58 to 672.68mbsf, leading Monechi & Reale (1997) to assign this interval to the latest Eocene *R. oamaruensis* Zone. Finally, the interval from 682.17 to 681.16mbsf was assigned to the Late Eocene *I. recurvus* Zone, based on the presence of the nominate taxon in the stratigraphically lowest sample of the interval. Samples from 682.17mbsf to the base of the hole (696.61mbsf) contained only rare reticulofenestrids and thoracospheres and could not be assigned reliably to a zone.

Wilson *et al.* (1998) used the data of Wei (1992), in conjunction with other palaeontological data, to calibrate a revised magnetostratigaphic record for CIROS-1. The chronologic framework they constructed for the lower portion was dependant on the calcareous nannofossil *I. recurvus*. Wilson *et al.* (1998) assumed that the stratigraphic lowermost and uppermost occurrences of *I. recurvus* in CIROS-1 represented the evolutionary appearance and extinction (respectively) of the species. Using this assumption, the magnetostratigraphic record from CIROS-1 was interpolated between these presumed biochronologic datums, and chrons assigned. Based on this extrapolation, the authors placed the Eocene/Oligocene boundary at approximately 415mbsf, implying almost 300m of glaciomarine sedimentary rock of Late Eocene age. The authors noted three distinct problems with their magnetochronology. First, their interpretation placed the extinction of *I. recurvus* in what was interpreted to be Chron C13n, as opposed to its usual placement in the slightly younger Chron C12r. They accounted for this by proposing an earlier extinction due to the deterioration of the Antarctic environment (Wilson *et al.*, 1998). Secondly, they noted that, although the Eocene/Oligocene boundary is largely characterised by reversed polarity, their record from CIROS-1 is dominantly normal. Finally, there are several short, reversed-polarity intervals in their interpretation that are not evident in the geomagnetic polarity time-scale of Cande & Kent (1992). Wilson *et al.* (1998) posited that these features may correspond to unidentified cryptochrons (or 'tiny wiggles').

The magnetostratigraphy proposed by Wilson *et al.* (1998) clearly is not a straightforward interpretation based on pattern matching. The uncertainties of the magnetostratigraphic interpretation are compounded by the sparse and sporadic biostratigraphic record, which served as the primary means of calibration. Since the biostratigraphic interpretation is crucial to this problem of pre-Oligocene glaciation, a re-examination of that record is in order.

3. Methods

Samples from the CIROS-1 core were prepared using standard smear-slide preparation protocol (Watkins & Villa, 2000). Slides were examined using light-microscopy at approximately 1250x. Approximately 500 fields of view (FOV) were scanned per slide. Due to the extreme paucity of specimens, no attempts were made to assess relative abundance of species for this paper. Preservation of the nannofossils was assessed using the following criteria: Good (little evidence of overgrowth or etching, no impairment of species identification); Moderate (clear evidence of overgrowth or etching, species identification usually not impaired); Poor (clear evidence of overgrowth or etching, species identification often impaired). Data are archived at the World Data Center-A for Paleoclimatology http://www.ncdc.noaa.gov/paleo/data.html (Watkins, 2007).

Assemblage counts from this study, and selected relative abundance counts from the Monechi & Reale (1997) dataset (see below), were converted to presence/absence data for analysis. Sample data was analysed using multivariate cluster analysis of a matrix of Euclidean distance measures between species. Analysis was performed using the *PAST* program, using Ward's method, as it tends to minimise the increase of within-group variance (Hammer *et al.*, 2001).

4. Results

A total of 133 samples were prepared and examined for nannofossils. Nannofossils were observed in 45 of these samples, while 88 of the samples were barren or essentially barren (no nannofossils in approximately 500 FOV). Nannofossil abundance in the 45 nannofossil-bearing samples is very low (generally <10 specimens per 500 FOV). Even in the most abundant assemblages, nannofossils never exceeded an average of one specimen per FOV. Preservation varied markedly from poor to excellent, although the average preservation was moderate to poor. Species richness is very low, with only 30 taxa in the entire dataset. The highest sample species richness value of 10 was observed in a single sample, although this assemblage included some clearly reworked forms, including Cretaceous (*Eiffellithus turriseiffelii* and *Watznaueria barnesiae*) and mid-Eocene (*Discoaster barbadiensis* and *Discoaster saipanensis*) taxa. The average sample species richness (excluding obviously reworked species) for the dataset is approximately three, and no slide had more than six species, if reworked taxa were excluded.

The examination of this sample set corroborated the data collected by Monechi & Reale (1997) in almost every respect. In several cases, the sample interval precisely corresponded to a sample from Monechi & Reale (1997). In such cases, a nearly identical assemblage was observed in the present study. Most notably, the reworking of Cretaceous and Lower Palaeogene taxa documented by Monechi & Reale (1997) was confirmed by the present observations. Since these two datasets were collected from two distinct sets of samples prepared in two different laboratories, the presence and nature of the obvious reworking of substantially older taxa cannot be ascribed to sample contamination, but must actually be a feature of the CIROS-1 assemblages.

Given the high fidelity of the dataset collected by Monechi & Reale (1997), 32 selected samples from their study were added to the 45 of the present study to augment the distribution of nannofossil-bearing samples.

Numerical or relative abundance data were not used for this analysis, due to the very low abundances, low species richness, and sporadic occurrences of nannofossils in these samples; instead, all data were converted into binary (presence/absence) form. R-mode multivariate cluster analysis yielded a solution with six distinct clusters of species (Figure 3), reflecting the recurrent associations of species in the dataset.

Cluster A contains three reticulofenestrids that occur throughout the lower section of CIROS-1. *Reticulofenestra daviesii* is the most common of these forms, and often is the only fossil preserved in the sparsest assemblages. The other two forms occur with less regularity, but are still represented throughout. These 'back-
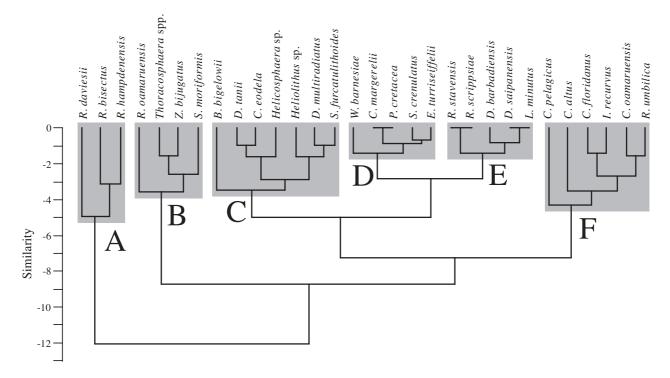

Figure 3: Results from the multivariate cluster analysis of nannofossil assemblages from CIROS-1

ground' reticulofenestrids span the late Middle Eocene through early Late Oligocene (approximately CP14-19a; Figure 4). Cluster B contains three long-ranging taxa (*Thoracosphaera* spp., *Sphenolithus moriformis* and *Zygrhablithus bijugatus*) and *Reticulofenestra oamaruensis*, which is restricted to the latest Eocene to earliest Oligocene (CP15b-16b).
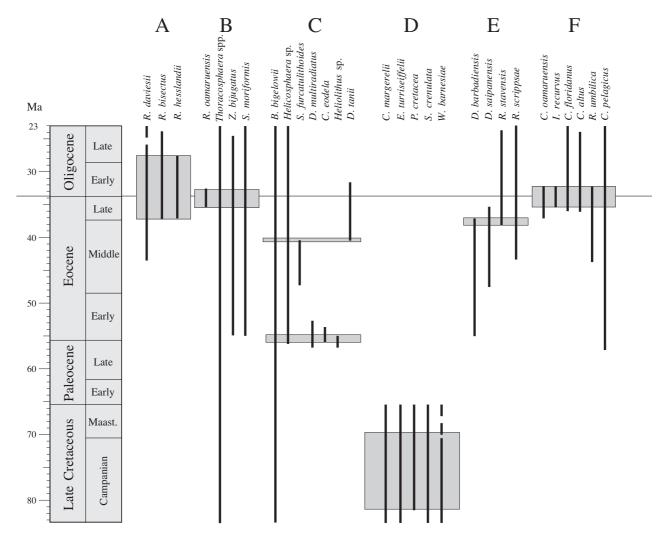
Cluster C is a mixture of several species of latest Paleocene to Middle Eocene age. *Campylosphaera eodela* and *Discoaster multiradiatus* co-occur in CP8b to CP9a, which straddles the Paleocene/Eocene boundary. *Discoaster tanii* and *Sphenolithus furcatulithoides* co-occur in CP14 (Middle Eocene). These relationships indicate that nannofossils in this cluster have sources from (at least) two distinct stratigraphic horizons (Figure 4).

Cluster D consists solely of Late Cretaceous taxa and is clearly reworked in this section. The most probable age for this assemblage is Campanian or latest Maastrichtian. The specimens of *Prediscosphaera cretacea* in CIROS-1 have the clearly disjointed cross-bar that is typical of

Campanian to Maastrichtian specimens. *Watznaueria barnesiae* is generally absent from Southern Ocean assemblages from the latest Campanian until the latest Maastrichian (Watkins *et al*., 1996).

Cluster E contains two discoasters (*D. barbadiensis* and *D. saipanensis*) that occur together from CP13 to CP15 in the temperate and tropical regions. These species disappear earlier from the Southern Ocean and are largely restricted to no higher than CP14 (*e.g.* Berggren *et al*., 1995). The first occurrence of *Reticulofenestra stavensis* occurs in CP14b, suggesting that this cluster probably represents strata from CP14b (Figure 4). Clusters D and E link together at a high degree of similarity (Figure 3), suggesting that they were both reworked into the area by a similar mechanism and/or from a similar provenance.

Cluster F contains a group of species that characterise the latest Eocene and earliest Oligocene of the Southern Ocean. The species with the best-defined biostratigraphic range of this cluster is *Isthmolithus recurvus* (CP15b-16c). Other taxa in this cluster, including *Chiasmolithus*

Figure 4: Biostratigraphic placement of the six nannofossil assemblage clusters. Age-ranges illustrated for individual clusters (shaded box) represent the minimum range necessary to explain the co-occurrence of the species in each cluster. Stratigraphic ranges are based on information from Perch-Nielsen (1985), Wei & Wise (1990), Watkins *et al*. (1996) and Wise *et al*. (2004)
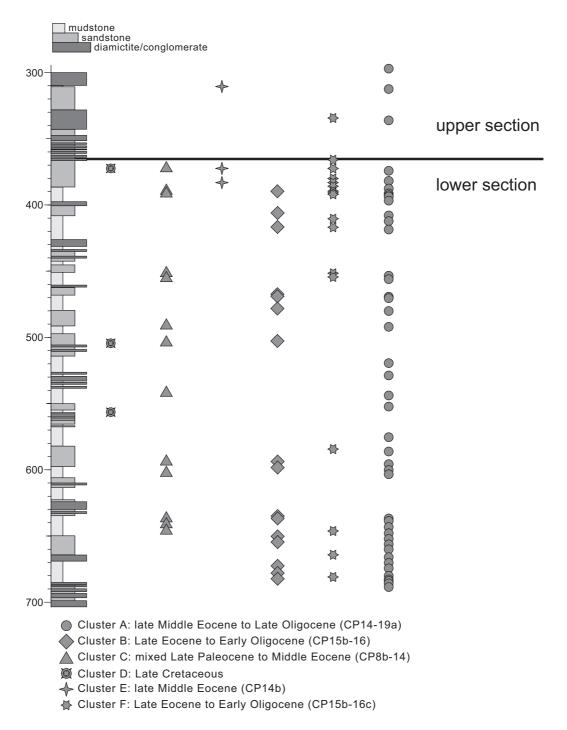
Figure 5: Stratigraphic distribution of nannofossil assemblage clusters from 300 to 702mbsf in CIROS-1

altus, *C. oamaruensis* and *Reticulofenestra umbilica*, have stratigraphic ranges that are consistent with the more restricted range of *I. recurvus*.

5. Discussion

The stratigraphic distribution of the clusters is illustrated in Figure 5. Clusters A, E and F occur in both the upper (0-366mbsf) and lower (366-702mbsf) sections, while the others are restricted to the lower section. Cluster A, consisting of 'background' reticulofenestrids, occurs in the lowest nannofossil-bearing sample at 686.9mbsf. Cluster

F, represented by *Isthmolithus recurvus*, is present as low as 681.2mbsf, indicating an age of latest Eocene to earliest Oligocene (CP15b-16) for this horizon. Cluster B, represented by *Reticulofenestra oamaruensis*, is present as low as 672.7mbsf, indicating a similar age of latest Eocene to earliest Oligocene (CP15b-16). Clusters C, D and E occur stratigraphically higher in the sequence, but have minimum ages that are older than that of *R. oamaruensis* or *I. recurvu*s. This is a clear indication that clusters C, D and E were reworked into the section.

Four of the species in Cluster C have known biostrati-

graphic ranges that are older than the maximum age of the CIROS-1 section (*Campylosphaera eodela*, *Discoaster multiradiatus*, *Sphenolithus furcatolithoides* and *Heliolithus* sp.). The other three taxa (*Braarudosphaera bigelowii*, *Discoaster tanii* and *Helicosphaera* sp.) have a pattern of occurrence that is similar enough (as measured by Euclidean distance) to the known reworked forms to be joined by Ward's method clustering. All five of the taxa in Cluster D have biostratigraphic ranges that terminate well below the base of the CIROS-1 section. Two species (*Discoaster barbadiensis* and *D. saipanensis*) in Cluster E clearly are reworked, while the other three species (*Lanternithus minutus*, *Reticulofenestra stavensis* and *R. scrippsae*) have sufficiently similar occurrence patterns to cluster with the reworked forms. In total, 37% (11/30) of the species must be reworked, while an additional 20% (6/30) appear to be reworked by association with these three clusters.

Clusters B and F are composed of species whose stratigraphic ranges are essentially the same. The cluster analysis clearly separated these two groups of species, however, indicating that they had distinctly different patterns of occurrence in the section. Inspection of the data indicates that this is the case. Representatives from these two clusters occur together in less than 10% (3/31) of the samples, and *I. recurvus* and *R. oamaruensis* never occur together in the same sample. The antithetical behavior of these two suggests an unusual situation. Such an alternation of markedly different assemblages could have resulted from an extraordinary palaeoecological separation, or one (or both) of the assemblages could be an allochthonous (reworked) component.

There is evidence of the reworking of Cluster B, based on the record from Cape Roberts Project (CRP) Site 2, located approximately 50km to the north of the site of CIROS-1 (Figure 1). Specimens of *R. oamaruensis* occur through a stratigraphic thickness of approximately 30m (444.8 to 474.6mbsf) in CRP2a. Evidence from diatom biostratigraphy (Scherer *et al*., 2000) and strontium isotopes (Lavelle, 2000) from this interval both indicate a significantly younger age (29.5-30Ma) than the youngest possible age (approximately 33.5Ma) for *in situ R. oamaruensis* (Watkins & Villa, 2000). Although such independent age constraints are not available for the CIROS-1 core, the well-documented reworking from nearby CPR2, coupled with the copious evidence of other reworking in CIROS-1 (Clusters C, D and E), strongly suggest that *R. oamaruensis* (and Cluster B) is a reworked component in CIROS-1. If this is the case, a further 13% (4/30) of the total species richness would be reworked.

Given the obvious reworking of Clusters C, D and E, and the probable reworking of Cluster B, the question arises as to whether any of the CIROS-1 nannofossils are in place. Comparison with the well-dated Oligocene composite record of nearby CRP holes suggests that the long-ranging reticulofenestrids of Cluster A, numerically dominated by *Reticulofenestra daviesii*, may represent the

nannofossil assemblages that inhabited the Victoria Land Basin during deposition of the lower portion of the CIROS-1 corehole. Similar 'background' assemblages occur throughout the nannofossil-bearing portions of the Lower Oligocene portion of CRP2 and CRP3, including in sediments that have other well-preserved siliceous and calcareous microfossils (Watkins & Villa, 2000; Watkins *et al*., 2001).

The species in Cluster F are conspicuous by their absence or rarity in the Cape Roberts section. Only one specimen each of *Coccolithus pelagicus* and *Chiasmolithus oamaruensis*, and only three specimens of *Chiasmolithus altus*, were recorded (Watkins & Villa, 2000; Watkins *et al*., 2001). *I. recurvus* and *R. umbilica* were not observed at all in the 149 nannofossil-bearing samples in the CRP composite section. This could be explained in one of two ways. The CRP section may not have had a source of the appropriate, *I. recurvus*-bearing strata from which to derive reworked specimens, whereas the CIROS-1 section did have such a provenance. Alternatively, the *I. recurvus*-bearing samples in the CIROS-1 section may represent multiple intervals of marine deposition that are not represented (or represented by barren sediment) at the CRP site. If the latter is true, however, there is no compelling reason that the marine deposition must have been during the Late Eocene, as opposed to the Early Oligocene.

6. Conclusions

Examination of the calcareous nannofossil record in the lower portion of the CIROS-1 core indicates that the assemblages are characterised by very low abundances, sporadic occurrences, and moderate to poor preservation. Quantitative analysis identified six clusters (recurrent assemblages) of nannofossils. Three of these clusters clearly were reworked in the section, including 11 taxa (37% of the total species richness) that must be reworked and six taxa (20% of the total richness) that are reworked by association. It is probable that a fourth assemblage was also a reworked component, which would add an additional four taxa (13% of the total richness) to the reworked component. These reworked nannofossils occur throughout the lower portion of CIROS-1, and are often the dominant fossil in a given sample.

There is no strong evidence as to whether the remaining nine taxa are reworked or not. Three of them (Cluster A) are common constituents of the assemblages from the nearby Cape Roberts Lower Oligocene strata that is, at least in part, correlative with the CIROS-1 strata, suggesting that they are stratigraphically in place. There is no clear evidence as to whether the remaining six species (Cluster F) are reworked or in place, although their nearly complete absence from the Lower Oligocene of CRP suggests they were not common constituents of surface-waters in this part of the Victoria Land Basin during the Early Oligocene. Even if Cluster F is autochthonous, it only establishes the age as latest Eocene to Early

Oligocene.

The preponderance of reworking throughout the lower portion of the CIROS-1 section casts strong doubt on the stratigraphic integrity of the occurrence of *Isthmolithus recurvus*, especially in terms of its use to establish a pre-Oligocene initiation of coastal (and therefore continental) glaciation on Antarctica. Given the wealth of evidence from multiple proxies in the deep sea that has been established during the decade since the excellent work of Monechi & Reale (1997), and the weakness for an Eocene age brought out by the present quantitative analysis, it is parsimonious to assign an Early Oligocene age to the lower portion of CIROS-1.

Acknowledgments

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