

Palaeogene Calcareous Nannofossils from CRP-2/2A, Victoria Land Basin, Antarctica

D.K. WATKINS¹ & G. VILLA²

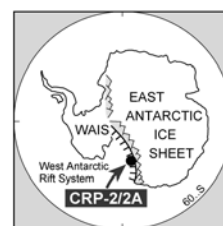
¹Department of Geosciences and University of Nebraska State Museum, University of Nebraska, Lincoln, Nebraska 68588-0340 - USA

²Dipartimento di Scienze della Terra, Università di Parma, Parco Area delle Scienze, 157, 43100 Parma - Italy

*Corresponding author (dwatkins@unlserve.unl.edu)

Received 6 October 1999; accepted in revised form 9 June 2000

Abstract - Rare calcareous nannofossils from the Cape Roberts Project drillhole CRP-2A indicate that this area was episodically invaded by marginal oceanic surface waters during the late and late early Oligocene. These depauperate assemblages lack most of the biostratigraphic index fossils for the Oligocene, but do provide two datums that aid in constraining the age of the section: the last appearance datum (LAD) of *Dictyococcites bisectus* (23.9 Ma) at 149.28 mbsf and the LAD of *Chiasmolithus altus* (26.1 Ma) at 412.25 mbsf. Calcareous nannofossil assemblages stratigraphically below c. 440 mbsf contain conspicuous evidence of reworking of older (late Eocene) specimens that renders age determination difficult.



INTRODUCTION

Calcareous nannofossils occur throughout the Southern Ocean in pre-Miocene sedimentary rocks deposited in pelagic and hemipelagic settings where the bottom was above the carbonate compensation depth (CCD). Conditions during the Cretaceous through Oligocene were sufficiently different in the Southern Ocean from the temperate and tropical areas of the world that separate biostratigraphical zonation have been developed. The Southern Ocean biostratigraphical zonation of Wei & Wise (1992) has been adopted to subdivide the Eocene and Oligocene sequence in the Cape Roberts cores (Fig. 1). This zonation has the advantage of utilizing several prominent high-latitude species while retaining those biostratigraphical marker species from temperate zonation that penetrate in the high Southern latitudes. Most of the biohorizons used in this zonation have been correlated directly to the palaeomagnetic time scale and, indirectly, to the geochronological time scale.

METHODS

The entire sequence from holes CRP-2 and CRP-2A was sampled and examined for calcareous nannofossils. Samples were chosen preferentially from fine-grained lithologies or at least from sedimentary rocks with fine-grained matrix material. All samples were examined initially by using smear slides of raw sediment. In most cases, no additional sample preparation was done. A few coarser-grained sediments were processed by a gravitational settling technique in which approximately 0.1 cm³ of sediment was disaggregated and suspended in sufficient purified water to constitute a column of approximately 2 cm height in a

small closed vial. This suspension was allowed to settle undisturbed for 60 seconds, at which point an aliquot of the supernatant was withdrawn and mounted on a cover glass. This procedure removed grains larger than approximately 20 microns from the supernatant, and thus concentrated the finer, nannofossil-bearing size fraction. Nannofossils occur in only some samples in the CRP-2A section. Even in these samples, nannofossils are an extremely rare sedimentary component (<<1%). As such, the traditional estimators of calcareous nannofossil abundance as a sedimentary component yield little information on relative abundance, as they all would be either B (Barren) or V (Very rare). The relative abundance of different calcareous nannofossil species was determined following criteria adopted by (Wei, 1992): C=common (1 specimen per 2-10 fields of view); F=few (1 specimen per 11-50 fields of view); R=rare (1 specimen per 51-200 fields of view at 1250x).

RESULTS

A total of 6 samples spanning the cored interval from 29.70 to 57.32 mbsf in CRP-2 and 179 samples from 54.67 to 624.10 mbsf in CRP-2A were examined for calcareous nannofossils. All of the samples from CRP-2 are barren of calcareous nannofossils. In total, 72 of the 179 samples from CRP-2A contain some nannofossils. This suggests a representation of nannofossils in less than 40% of the cored interval. However, examination of figure 2 indicates that the distribution of nannofossil-bearing samples in the section is not uniform, but occurs with nannofossiliferous intervals separated by barren intervals. For example, the 25 m from c. 144 to 169 mbsf contains nannofossils in 90% of the samples (18 out of 20), whereas the subjacent 25 m from c. 169 to 194 mbsf contains nannofossils in only 11% of the

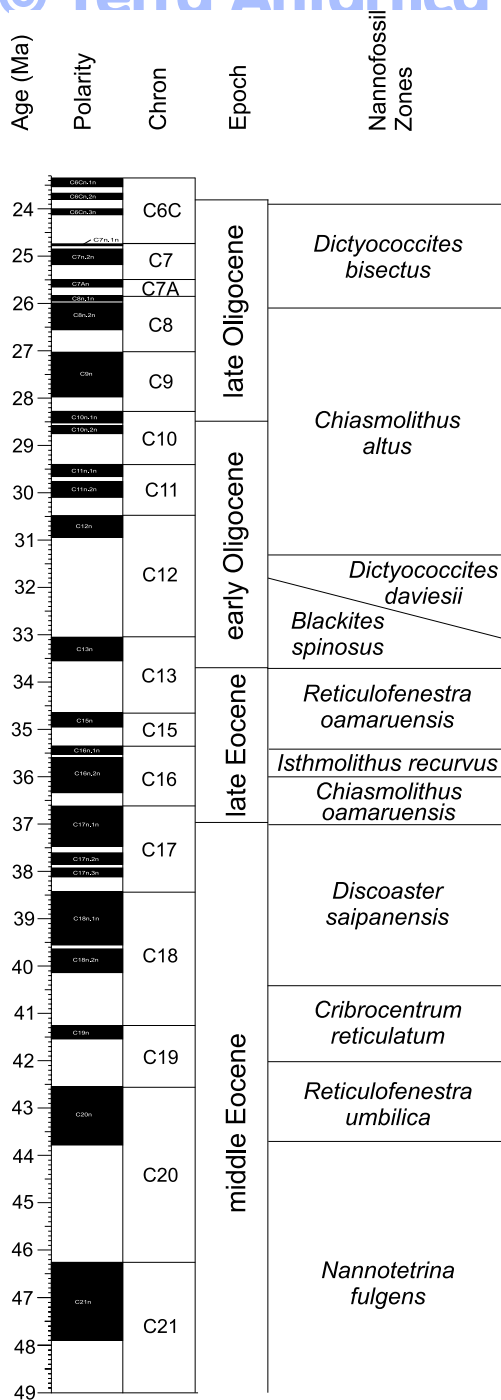


Fig. 1 - Calcareous nannofossil biostratigraphic zonation for the upper Palaeogene of the Southern Ocean and Antarctic region (after Wei & Wise, 1992) correlated to the Magnetic Polarity Time Scale of Berggren et al. (1995).

samples (one out of nine). These intervals of nannofossil-bearing samples define a set of hemipelagic depositional episodes (see below) that punctuate the Oligocene history of the Ross Sea. These fossiliferous intervals occur generally in the finest-grained mudrocks.

The highest of these stratigraphical intervals, (144.44 to 167.35 mbsf) constitutes an interval of relatively continuous nannofossil occurrence. Excluding the barren samples intercalated within this sequence, the average nannofossil species richness is 3.3 species per sample. The highest richness values occur near the centre of the sequence (150.70

to 155.20 mbsf), with two samples having seven species per sample (Tab. 1). Specimen abundance and species richness decrease both up-section and down-section from this richness maximum. These assemblages are dominated by moderate to small-size reticulofenestrids including *Dictyococcites hesslandii*, *Dictyococcites productus*, and *Dictyococcites bisectus*. It should be noted that the latter are all *D. bisectus* s.s. (the “small morphotype”), and no specimens of *Dictyococcites stavensis* (sometimes known as the “large morphotype”) are present. The presence of *D. bisectus* without *Chiasmolithus altus* is indicative of the *Dictyococcites bisectus* Zone of late Oligocene age. The last occurrence of *D. bisectus* is well constrained in the Southern Ocean (Wei & Wise, 1992; Berggren et al., 1995) at 23.9 Ma. This datum (identified at 149.28 mbsf) may be a minimum estimate for the age of this horizon, as this species is only present in this sequence during the interval of highest species richness. However, inspection of the age model for CRP-2/2A (Wilson et al., this volume) suggests that this form is quite near the youngest part of its range (ca. 23.9 to 24.4 Ma). The late Oligocene age is corroborated further by the presence of *Reticulofenestra minuta*. McIntosh (this volume) reports that a pumice concentration near 193 mbsf yields an $^{40}\text{Ar}/^{39}\text{Ar}$ date of 23.98 ± 0.13 Ma. This dated horizon lies c. 43.7 metres below the LAD of *D. bisectus*. This strongly suggests that this is a “true” last appearance, as opposed to a local premature ecological exclusion.

The interval from 169.58 to 193.65 mbsf is characterized by samples that are largely barren of calcareous nannofossils. Only one sample, at 181.74 mbsf, contains rare, moderately preserved nannofossils. Species present include *D. hesslandii*, *D. bisectus*, *Dictyococcites daviesii*, and *R. minuta*. This assemblage is consistent with the *D. bisectus* Zone of late Oligocene age.

Calcareous nannofossils occur consistently in samples from the short interval of 195.70 to 200.54 mbsf. All four samples taken from this interval contain rare, moderately preserved assemblages consisting of three to six taxa (Tab.1). The most species-rich sample, from 200.15 mbsf, contains the smaller reticulofenestrids (*R. minuta* and *R. minutula*) as well as the larger dictyococcitids (*D. daviesii*, *D. hesslandii*, and *D. productus*), but significantly lacks *D. bisectus*. In addition, it contains *Thoracosphaera saxae*, a calcareous dinoflagellate. The assemblage is consistent with, but not definitive of, the *D. bisectus* Zone of late Oligocene age.

Below this short interval of nannofossil-bearing rock, there is a thick (at least 115 m) sequence of strata that is largely devoid of calcareous nannofossils (Fig. 2). From 215.52 to 330.26 mbsf, it yielded only five samples (222.3, 236.3, 245.5, 296.4, and 296.8 mbsf) that contain very rare, generally poorly preserved nannofossils. Because of the very rare occurrence of these specimens in a thick sequence of otherwise barren sedimentary rock, it is entirely probable that the specimens are reworked. None of the depauperate assemblages are age diagnostic. It is notable, however, that they contain the last downhole occurrence of *R. minuta* (at 296.83 mbsf). This last occurrence is the lowest nannofossil-bearing unit above a prominent disconformity at 306.7 mbsf.

Tab. 1 - Continued.

Sample	Abundance	Preservation	<i>Bicolummus ovatus</i>	<i>Chiasmolithus altus</i>	<i>Diacyococites bisectus</i>	<i>Diacyococites daviesii</i>	<i>Diacyococites hesslandii</i>	<i>Diacyococites productus</i>	<i>Isthmolithus recurvus</i>	<i>Reticulofenestra hampdenensis</i>	<i>Reticulofenestra minuta</i>	<i>Reticulofenestra minutula</i>	<i>Reticulofenestra oamaruensis</i>	<i>Reticulofenestra umbilicatus</i>	<i>Sphenolithus</i> sp. cf. <i>S. moriformis</i>	<i>Thoracosphaera</i> sp.	<i>Thoracosphaera heimii</i>	<i>Thoracosphaera saxea</i>	sp. indet. A	<i>Triquetrorhabdulus</i> sp. indet.	species richness
465.00	R	M			R	C				R			R	?							4
466.24	VR	P					R														1
467.24	R	M					R						R								2
467.76	R	P			R		R														2
468.73	F	M			R	F				R			R								4
471.00	R	P					R												R		2
471.11	R	M					R														2
472.66	F	M					R			R								R			4
474.63	R				R		R						R								3
478.29	R					R															1
481.69	VR	M					R														1
486.30	B																				0
486.86	B																				0
500.08	B																				0
502.67	B																				0
504.64	B																				0
506.03	B																				0
507.88	B																				0
508.70	B																				0
510.22	B																				0
523.68	B																				0
524.44	B																				0
529.75	B																				0
531.65	B																				0
536.60	B																				0
543.85	B																				0
547.54	B																				0
548.61	B																				0
556.92	B																				0
559.14	B																				0
564.68	B																				0
568.10	B																				0
575.50	B																				0
584.57	B																				0
604.60	B																				0
611.96	B																				0
612.97	B																				0
619.11	R	P					R														1
623.03	B																				0
623.39	B																				0
623.60	F	M	R		F		F							R		R					4
624.10	B																				0

All nine samples taken from the interval 330.69 to 340.19 mbsf contain calcareous nannofossils, although surrounding rocks immediately above and below are barren. The assemblages are similar to others higher up-section, containing *D. bisectus*, *D. daviesii*, and *D. hesslandii*. In addition, thoracosphaerids occur in samples 330.82 and 340.00 mbsf. This section is underlain by another thick (c. 70 metres) interval of rock that is largely barren of nannofossils. From 340.28 to 410.94 mbsf, only five samples (358.22, 396.98, 397.92, and 409.38 mbsf; Tab. 1) contain nannofossils. The assemblages are generally poorly preserved and contain only very rare nannofossils including *D. daviesii* and *D. hesslandii*. In addition, however, a sample at 358.49 mbsf contains common fragments of *Thoracosphaera heimii* and *Thoracosphaera saxea*, mainly

as single platelets, representing thoracosphaerid tests that have been broken. No other nannofossils are present. This thoracosphaerid-rich interval is reminiscent of the thoracosphaerid horizons in the Quaternary of CRP-1. Villa & Wise (1998) related the Quaternary occurrences in CRP-1 to relatively warm intervals during an otherwise glacially dominated climatic regime. However, this deduction may not be applicable directly to this late Oligocene occurrence.

The thin siltstones interbedded with coarser lithologies from 412.25 to 413.05 mbsf contain *Chiasmolithus altus*, in addition to *D. daviesii*, *D. hesslandii*, and *R. hampdenensis*. The last appearance datum (LAD) of *C. altus* has been well documented from other areas in Chron C8n at 26.1 Ma (Berggren et al., 1995). The LAD of *C. altus* is used as the

upper boundary of the *C. altus* Zone of late early to early late Oligocene age. This species appears to range down to a first appearance in the early Oligocene (Perch-Nielsen, 1985; DeKaenel & Villa, 1996), although Wei & Wise (1990) report this taxon significantly lower (late to middle? Eocene) in the Weddell Sea. This species has been found in only two samples during our preliminary examination of CRP-2A, suggesting that a significant part of the zone is missing. Diatom evidence (Scherer et al., this volume) suggests that this interval is early late Oligocene in age, thus indicating the upper part of the zone, although temporal constraint of the entire interval from approximately 310 through 438 mbsf is rather poor.

Samples in the interval from 426.5 to 449.4 mbsf are difficult to date biostratigraphically using calcareous nannofossils. All but three of the samples examined from this interval are either barren or contain such very rare, poorly preserved nannofossils that biostratigraphical classification is impossible. Three samples having somewhat better assemblages still evidently lack any diagnostic species. This interval can be characterized only by its stratigraphical relationship with the overlying (*C. altus*) zone, and, on account of its position it is assigned tentatively to the combined *Dictyococcites daviesii/Blackites spinosus* Zone of early Oligocene age. The two zones have been combined because the biohorizon used to differentiate the two, the LAD of *Isthmolithus recurvus*, was not identified in our examination. This might suggest that the entire interval should be placed in the *D. daviesii* Zone.

The interval from 449.35 to 474.63 mbsf is characterized by well-preserved assemblages containing *Reticulofenestra oamaruensis*. This high southern latitude species has a total range that defines the *R. oamaruensis* Zone of earliest Oligocene to latest Eocene age and is well-documented geochronologically. The FAD of *R. oamaruensis* appears to occur consistently in Chron C16 in the Southern Ocean (Wei & Wise, 1992), with its best placement within C16n. In (Berggren et al., 1995), yielding an age of 35.4 Ma. The LAD of *R. oamaruensis* has been correlated to Chron 13r, although it may occur at the C13n/C13r boundary based on the record at ODP Site 699 (Wei, 1991; Berggren et al., 1995). Given this placement in C13r, it has been assigned an age of 33.7 Ma by (Berggren et al., 1995), which is numerically the age of the Eocene/Oligocene boundary as used by them. However, if the record of ODP Site 699 is correct, the actual age of the LAD of *R. oamaruensis* should be slightly higher. Berggren et al. (1995) date the Chron C13n/C13r boundary at 33.545 Ma. This earliest Oligocene age assignment is appealing as it is more in keeping with the traditional assignment of the zone as straddling the Eocene/Oligocene boundary.

In CRP-2A, there is significant evidence from strontium isotopes and diatoms that indicates that the specimens of *R. oamaruensis* are reworked. Lavelle (this volume) reports strontium isotope ages of 29.4, 29.6, and 29.9 Ma from molluscan fragments at depths of 445.0, 460.6, and 463.4 mbsf, respectively. These samples are denoted as S6, S7, and S8, respectively, in Wilson, Bohaty et al. (this volume). Even given the possibility of a LAD of *R. oamaruensis* at the Chron 13n/13r boundary, these strontium-isotope age determinations are more than 3.5 m.y. younger than those

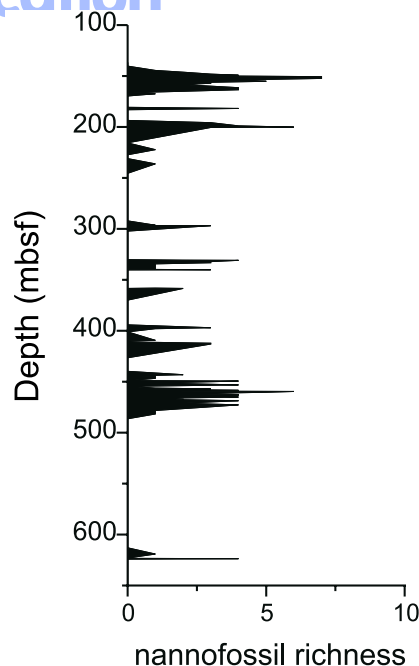


Fig. 2 - Species richness of calcareous nannofossil assemblages from CRP-2/2A. Horizontal axis is the number of species identified in a given sample. Note that the distribution of nannofossil-bearing samples is non-random, defining a set of hemipelagic episodes during deposition of the Oligocene of CRP-2A (see text).

implied by nannofossil biostratigraphy. The association of diatoms in this interval also indicates a younger age compatible with the strontium-isotope evidence (Scherer et al., this volume). Clearly, these *R. oamaruensis* specimens are reworked.

There is a thick interval of rock that is barren of calcareous nannofossils from 486.30 to 612.97 mbsf. Nevertheless, near the base of the hole, two samples yielded calcareous nannofossils. At 619.11 mbsf, a sparse, poorly preserved assemblage contains only *Dictyococcites heslandii*. A significantly better assemblage was recovered from the basal "fast track" sample at 623.60 mbsf that includes *Bicolumnus ovatus*, *Dictyococcites bisectus*, and *D. heslandii*. *Bicolumnus ovatus* was first described from the upper Eocene and lower Oligocene of Maud Rise, Weddell Sea but is also known to occur from the upper Eocene and lower Oligocene of the Falkland Plateau and Rio Grande Rise (Wei & Wise, 1992). More recently, it has been reported from as high as the upper Oligocene (Zone NP 25) of the Iberian Abyssal Plain (DeKaenel, & Villa, 1996). Thus, the species present in this assemblage cannot be used to assign an age for the base of CRP-2A.

THE SIGNIFICANCE OF NANNOFOSSIL OCCURRENCE

The extremely rare nannofossils that occur in the CRP-2A section are characterized by low species richness, low diversity, and domination of the assemblages by reticulofenestrid placoliths. These depauperate nannofossil assemblages indicate that marginal conditions for calcareous nannoplankton existed during the Oligocene in

McMurdo Sound. The almost total lack of sphenoliths and the absence of discoasters indicate very cool surface waters near the lower thermal limits for nannoplankton growth and propagation. Because of the rarity of nannofossils in general, little can be derived from quantification of abundances. However, species richness (number of species per sample) does yield useful information about the relative character and abundance of the assemblages.

Examination of figure 2 indicates the non-uniform distribution of calcareous nannofossils in the sequence. As discussed above, distinct pulses of presence are separated by many samples that lack calcareous nannofossils. As the skeletal elements of marine phytoplankton, calcareous nannofossil presence and abundance should correspond to the relative influence of oceanic surface waters at the site of deposition. Nannofossil absence has little significance in glaciomarine sedimentary rocks such as those in the upper Palaeogene at Cape Roberts. High rates of sediment accumulation, as are often associated with glaciomarine environments, can dilute thoroughly the calcareous biogenic component so that essentially they disappear even in areas with wholly oceanic surface waters. Cold, corrosive water at the sediment-water interface, typical of the high latitudes, can destroy calcareous nannofossils even in areas of relatively high coccolith production. Thus, the absence of calcareous nannofossils in large portions of the CRP-2A section reveals little about the depositional environment.

By the same token, the sporadic and very rare presence of calcareous nannofossils in parts of the CRP-2A sequence cannot be interpreted unequivocally as a signal of surface water productivity. Several possibilities exist and can be tested, at least in some degree. One possibility is that the pulses in nannofossil presence record episodes of invasion of open oceanic surface waters into the proximal Ross Sea. A second possibility is that these pulses record episodes of decreased sediment accumulation rates, resulting in decreased dilution of the biogenic input from the surface waters. A third possibility is that these pulses indicate diagenetic variability. Finally, it is possible that these pulses actually record episodes of reworking of older calcareous nannofossils. Each of these possibilities are discussed, in turn, below.

The possibility of reworking is of paramount importance, as when evidence of reworking occurs, the other possibilities become moot. As discussed above, there is strong evidence that the *Reticulofenestra oamaruensis* specimens in samples from 449.4 through 474.4 mbsf are reworked. Given that reworking, it is difficult to assess whether the rest of the assemblage in these samples is also reworked. These are rather unusual assemblages. Comparison with assemblages from the *R. oamaruensis* Zone of Leg 120 indicates significant differences in assemblage composition. The open ocean assemblages from Kerguelen Plateau contain common *Isthmolithus recurvus* as well as *Chiasmolithus oamaruensis*. Neither of these taxa have been reliably identified from these assemblages in CRP-2A. Indeed, if *R. oamaruensis* were deleted from these assemblages, there is no significant difference between these and the assemblages that occur at depths less than 400 mbsf.

The role of diagenesis does not appear to solely control nannofossil presence and richness, although it is difficult to determine the true extent of its influence on the microfossil record. Calcareous content of the sediment varies appreciably throughout the section, but this is not due to the contribution of pelagic carbonate. There are long intervals in the core that are barren of oceanic microplankton fossils but which contain relatively well-preserved macroinvertebrate carbonate. Sampling around and inside of the best-preserved calcareous macrofossils often did not yield calcareous nannofossils. In addition, there were relatively few samples in CRP-2A with poor preservation (Table 1). When calcareous nannofossils are present, they tend to be well preserved. Of course, it is possible that the rarity of nannofossils led to a simple binary diagenetic history where either the rare nannofossils were well preserved (essentially no diagenesis) or they were totally eliminated from the sedimentary rock.

In the strict sense, it is difficult to separate fully the effects of possibilities one and two above. Oceanic invasion episodes could easily be masked by prevailing high sediment accumulation rates. Two lines of analysis yield some information on the relative importance of these variables: comparison of nannofossil richness with sedimentary particle size distribution, and the comparison of diatom abundance with nannofossil richness.

Data for grain-size distribution are from the Cape Roberts Science Team (1998). Comparison of nannofossil richness and sediment grain size cannot be rigorously compared statistically because they are derived from different sample sets. However, broader trends are clear in examination of the comparison graphs (Fig. 3). It is most likely that clay, of all the sediment grain size classes, should correlate with nannofossil richness, as they have similar hydrodynamic characteristics. In addition, oceanic microplankton such as nannoplankton are usually associated with the offshore quiet water environments where clay is the principal terrigenous clastic particle. Lastly, clay-rich sedimentary facies often tend to yield the best preserved calcareous nannofossils. In the case of CRP-2A, however, there is no clear correspondence between these two components (Fig. 3A). Of the three largest peaks in clay percentage (where clay content exceeds c. 30%), only the peak between c. 454 and 467 mbsf appears to correspond to a peak in calcareous nannofossil richness. Conversely, with the exception of the aforementioned peak in nannofossils between c. 458 and 473 mbsf, none of the larger peaks in nannofossil richness correspond to increased clay content. The silt record (Fig. 3B) has more short-term variation ("noise") but appears to illustrate a similar relationship with nannofossil richness. Again, only the peak in nannofossil richness between c. 458 to 473 mbsf appears to correspond with elevated silt contents. The sand record from CRP-2A (Fig. 3C) indicates little positive correlation between sand content and nannofossil richness. This is an expected result, as the conditions that would promote high sand content in this glaciomarine environmental setting would not have promoted prolific nannofossil standing crops, and the high rate of sediment accumulation rates of many of the sandy facies would severely dilute the sedimentary contribution of biogenic

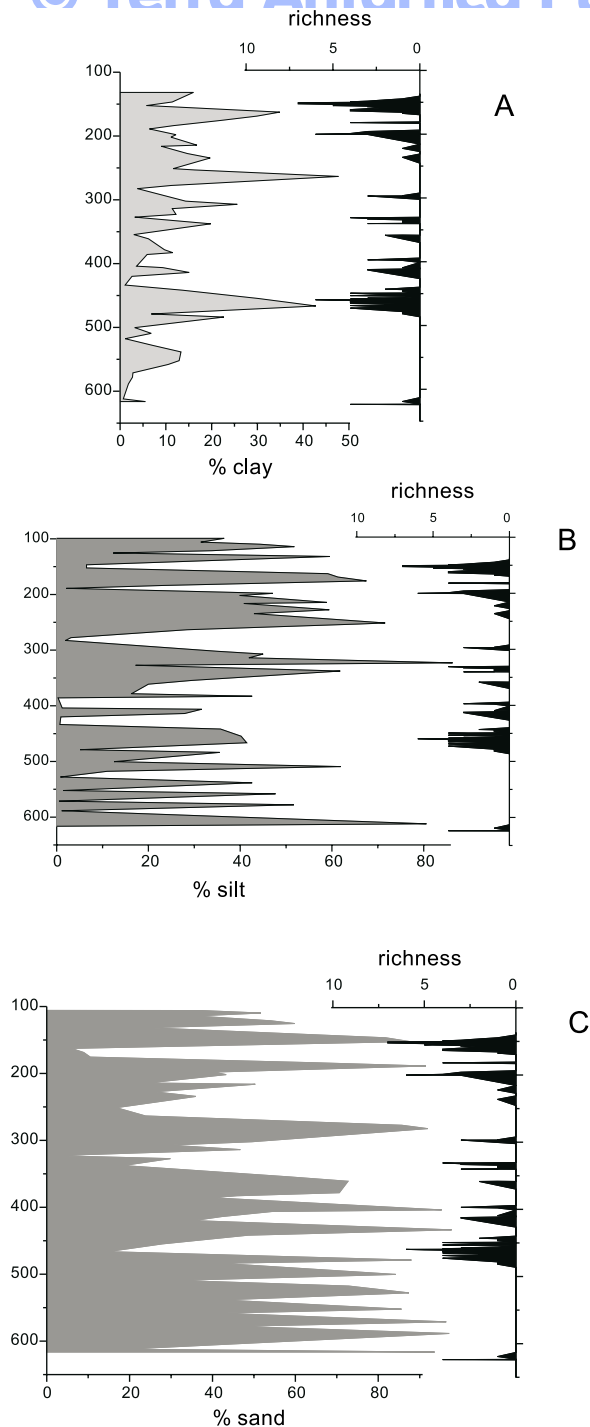


Fig. 3 - Comparison of nannofossil richness with sedimentary grain-size components: 3A compares % clay to richness; 3B compares % silt to richness; and 3C compares % sand with nannofossil richness. Grain-size data are from the Cape Roberts Science Team (1998).

carbonate. Finally, the inherent higher porosity and permeability of these sandy lithologies would promote movement of diagenetic fluids that would degrade or destroy pelagic biogenic carbonate.

Comparison of nannofossil species richness and diatom abundance indicates a complex relationship. Because of the difference in the distribution between nannofossil and diatom samples, rigorous statistical analysis is not possible. However, graphical comparison of the two groups (Fig. 4)

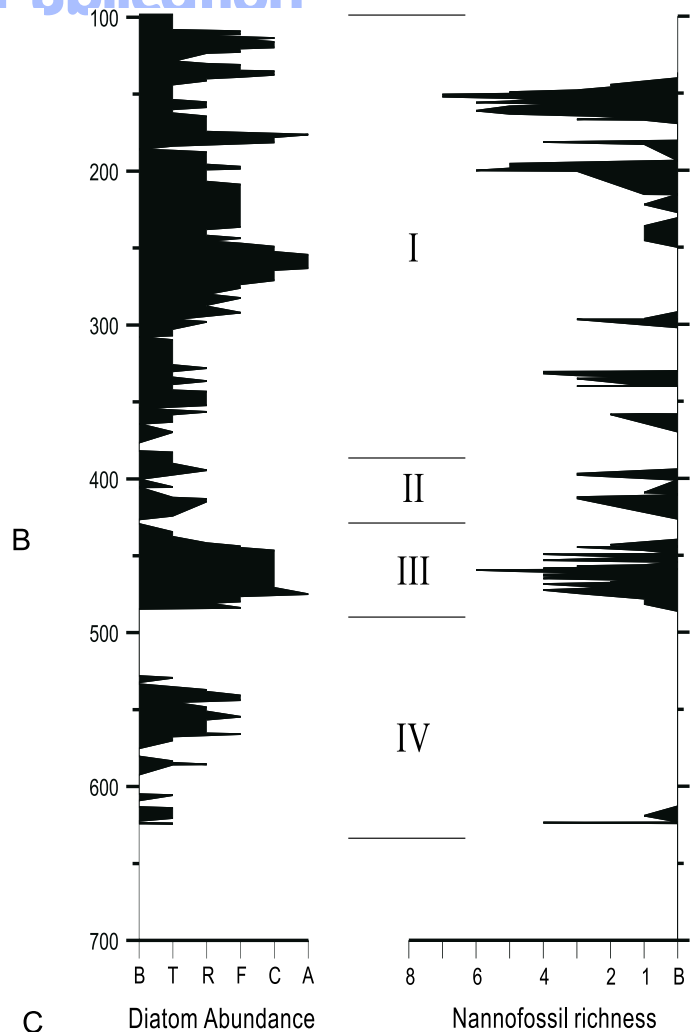


Fig. 4 - Comparison of nannofossil richness and diatom abundance. Diatom abundance is expressed as follows: B=barren; T=trace; R=rare; F=few; C=common; and A=abundant. Diatom abundance data is courtesy of Rusty Divine. Analysis of the relationship between diatom abundance and nannofossil richness suggest informal division of the section into four segments, numbered I-IV.

lends itself to qualitative analysis. The stratigraphic column is divided into four segments (I-IV) based on the pattern of behaviour between these two phytoplankton groups.

Segment I indicates a clearly antithetical behaviour pattern for the two groups. Diatom abundance maxima at 116-119, 135-137, 176, and 250-270 mbsf correspond to barren intervals in the nannofossil record. By the same token, nannofossil richness peaks at 148-164, 198-201, and 330-340 mbsf correspond to intervals where diatoms occur only as rare or trace components. This is not an unexpected result for *in situ* assemblages. Calcareous nannofossils, in general, are adapted to live in oligotrophic surface water conditions (Ziveri et al. 1995), whereas diatoms thrive under mesotrophic or eutrophic surface water conditions (Sancetta, 1996). Given this relationship, and the general correspondence of the diatom and nannofossil assemblages in biostratigraphic terms, it is parsimonious to conclude that the calcareous nannofossil assemblages in Segment I are in place. A similar argument can be made for Segment IV, although most of this segment is characterized by samples that contain neither diatoms nor nannofossils.

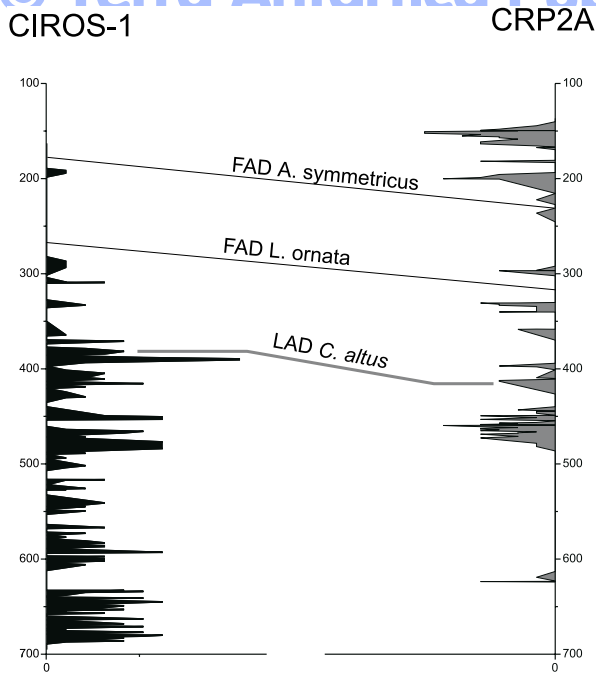


Fig. 5 - Comparison of the nanofossil species richness in CIROS-1 and CRP-2A. Data from CIROS-1 compiled from Edwards & Waghorn (1989), Wei (1992), Monechi & Reale (1997), and unpublished data of Watkins. Position of biostratigraphic lines of correlation based on Scherer et al. (this volume) and Wilson et al. (this volume) for the two diatom datums (FAD *A. symmetricus* and FAD *L. ornata*) and from Watkins (unpublished data and herein) for LAD *C. altus*.

Segment III contains nanofossil assemblages with clear biostratigraphic evidence of reworking. It is interesting, therefore, to see the correspondence of abundance and richness for the two microfossil groups in the segment. Common to abundant diatom assemblages and relatively rich nanofossil assemblages both occur in this segment. Although it is possible that this high microfossil content is the result of relatively lower rates of sediment accumulation (*i.e.*, lack of dilution by terrigenous influx), the presence of demonstrable reworking of nanofossils suggests a different mechanism occurred during deposition. Two possibilities suggest themselves for this segment. First, the older nanofossils were being eroded from subsea outcrops by more vigorous (local) circulation. This invigorated circulation promoted higher upwelling and mixing of nutrient-rich waters, stimulating enhanced diatom productivity. The second possibility is that the older nanofossils were eroded from land-based outcrops and carried out into McMurdo Sound, probably by stream and river flow rather than glacial ice. This riverine source might have provided higher nutrients into the surface water of McMurdo Sound, enhancing diatom productivity.

A similar pattern of correspondence between diatom abundance and nanofossil species richness seems to have occurred in Segment II. In this interval, two peaks of nanofossil richness correspond with two increases in diatom abundance. However, the diatom abundance is still low ("rare") in these two local maxima. In addition, the nanofossil assemblages are not very rich (2-3 taxa). It seems more likely that this pattern is depositional and preservational, with microfossils indicating intervals of

more open oceanic surface-water conditions accompanied by taphonomic and diagenetic conditions favoring the preservation of the relatively rare biogenic material in the sediment.

Thus, the relationship between diatom abundance and nanofossil richness suggests that most of the nanofossil assemblages in CRP-2A are in place, with the notable exception of those *R. oamaruensis*-bearing assemblages from *c.* 449 to 474 mbsf. Comparison with the sediment grain size shows no clear trends except that the interval with reworked assemblages (*c.* 449 to 474 mbsf) is characterized by high content of fine-grained terrigenous clastics (clay and, to a lesser extent, silt).

COMPARISON TO THE UPPER OLIGOCENE OF CIROS-1

The identification of calcareous nanofossil assemblages of the late Oligocene *Dictyococcites bisectus* Zone distinguishes this sequence in CRP-2A from others in the Ross Sea. Direct comparison with others in the Ross Sea is difficult because of the lack of previous work on upper Oligocene nanofossils. Interest in the CIROS-1 core focused on the lower Oligocene and upper Eocene. Edwards & Waghorn (1989) reported 15 nanofossil-bearing samples out of 35 total samples. They did report the presence of very poorly preserved *Reticulofenestra* sp. cf. *R. scrippsae* at 273.8 and 316.3 mbsf. The latter sample was reported to also contain *Reticulofenestra* sp. cf. *R. bisecta*. Edwards & Waghorn (1989) ascribed these occurrences to reworking based on the poor preservation and extreme rarity of the specimens. Wei (1992) did not report on any samples above CIROS Lithological Unit 18 (highest samples at 380.00 mbsf). Monechi & Reale (1997) sampled CIROS-1 Lithological Units 11 (four samples between 214.55 and 228.83 mbsf) and 15 (310.45 and 316.34 mbsf), dated by diatoms as late Oligocene in age (Harwood et al., 1989). However, these samples were barren of nanofossils. The stratigraphically highest sample previously known to contain nanofossils in CIROS-1 is from Lithological Unit 16, at 334.37 mbsf, with rare, poorly preserved specimens of *Coccolithus pelagicus* and *D. daviesii* (Monechi & Reale, 1997).

A re-examination of the CIROS-1 core above 340 mbsf (Unit 16) indicates several additional occurrences of calcareous nanofossils. The sample set used was collected by Prof. David M. Harwood for diatoms and other siliceous phytoplankton fossils. A single specimen of *Chiasmolithus altus* was observed in a sample from 162.5 mbsf. This is considered to be reworked based on its isolated nature and its occurrence outside its normal stratigraphic range. Three pairs of samples contain calcareous nanofossils in the underlying 180 m of upper Oligocene strata (Fig. 5). Samples from 193.2 and 195.7 mbsf both contain very rare but well-preserved specimens of *D. daviesii*. Similarly, samples at 288.4 and 294.68 mbsf each contain numerous *D. daviesii*. The lowest couplet of samples contains a more diverse assemblage including *D. daviesii*, *D. stavensis*, and *D. hesslandii*, as well as a small reticulofenestrid similar to *R. minuta*. It is clear from this comparison

that nannofossils were more common during the late Oligocene at Cape Roberts than at CIROS-1. This is not unexpected, as the Cape Roberts site was approximately 50 km northward and closer to the open oceanic water of the Ross Sea. It is tempting to attempt to correlate specific richness peaks between the sites, however the temporal control between these two holes is too coarse to yield unique or robust solutions. Below the LAD of *C. altus*, direct comparison of the nannofossil richness is rendered impossible by the apparent lack of correlation of the two sections (Wilson, Bohaty et al., this volume; Scherer et al., this volume).

CONCLUSIONS

Rare calcareous nannofossils occur in several intervals of the CRP-2A core. Two well defined biostratigraphic horizons occur within the sequence, LAD of *R. bisecta* and LAD of *C. altus*, that constrain the age of the section. These depauperate assemblages suggest that marginal surface-water conditions existed at times in McMurdo Sound during the Oligocene. One prominent interval of reworking of older nannofossils occurs at c. 449 to 474 mbsf, where latest Eocene *R. oamaruensis* is recycled into lower Oligocene sediments. The high influx of fine-grain terrigenous clastics and the high abundance of diatoms during this interval suggest either significant riverine transport of recycled nannofossils and nutrients or an episode of enhanced upwelling and erosion of subsea outcrops. Comparison with diatom abundance and grain size analyses suggests that the rest of the nannofossil assemblages (largely above 440 mbsf) are in place.

ACKNOWLEDGEMENTS

The authors wish to thank the organizers of the Cape Roberts Project for inviting them to participate in this interesting endeavor on the frontiers. It has been great fun. Funding for our efforts were provided by the National Science Foundation OPP-9419770 (to DKW). The authors wish to thank Ian Raine, Sherwood W. Wise, Jr., and Tony Edwards for their careful and challenging reviews that significantly improved the quality of the final manuscript.

REFERENCES

- Berggren W.A., Kent D.V., Swisher C.C. & Aubry M.P., 1995. A revised Cenozoic geochronology and biostratigraphy. In: Berggren W.A., Kent D.V., Aubrey M.P. & Hardenbol J. (eds), *Geochronology, Time Scales and Stratigraphic Correlation, Society of Economic Paleontologists and Mineralogists, Special Publication*, **54**, 129-212.
- Cape Roberts Science Team, 1998. Quaternary strata in CRP-1, Cape Roberts Project, Antarctica. *Terra Antarctica*, **5**(1), 31-61.
- DeKaenel E. & Villa G., 1996. Oligocene/Miocene calcareous nannofossil biostratigraphy and paleoecology from the Iberia Abyssal Plain, Northeastern Atlantic. *Proceedings of the Ocean Drilling Program, Scientific Results*, **149**, 79-145.
- Edwards A.R. & Waghorn D.B., 1989. Calcareous nannofossils. In: Barrett P. (ed.), *Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound, DSIR Bulletin*, **245**, 145-149.
- Harwood D.M., Barrett P.J., Edwards A.R., Rieck H.J. & Webb P.N., 1989. Biostratigraphy and chronology. In: Barrett P. (ed.), *Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound, DSIR Bulletin*, **245**, 231-239.
- Monechi S. & Reale V., 1997. Calcareous Nannofossil Assemblages of the CIROS-1 Core (Ross Sea): Further Assessments on Age. *Terra Antarctica*, **4**(2), 89-102.
- Perch-Nielsen K., 1985. Cenozoic calcareous nannofossils. In: Bolli H.M. et al. (eds), *Plankton stratigraphy*, Cambridge, Cambridge University Press, 427-554.
- Sancetta C., 1996. Laminated diatomaceous sediments: controls on formations and strategies for analysis. In: Kemp A.E.S. (ed.), *Paleoclimatology and Paleoceanography from Laminated Sediments, Geological Society Special Publication*, **116**, 17-23.
- Villa G. & Wise S.W., Jr., 1998. Quaternary calcareous nannofossils from the Antarctic Region. *Terra Antarctica*, **5**(3), 479-484.
- Wei W., 1991. Middle Eocene-lower Miocene calcareous nannofossil magnetobiochronology of ODP holes 699A and 703A in the subantarctic South Atlantic. *Marine Micropaleontology*, **18**, 143-165.
- Wei W., 1992. Updated nannofossil stratigraphy of the CIROS-1 core from McMurdo Sound (Ross Sea). *Proceedings of the Ocean Drilling Program, Scientific Results*, **120**, 1105-1117.
- Wei W. & Wise S.W., Jr., 1990. Middle Eocene to Pleistocene calcareous nannofossils recovered by Ocean Drilling Program Leg 113 in the Weddell Sea. *Proceedings of the Ocean Drilling Program, Scientific Results*, **113**, 639-666.
- Wei W. & Wise S.W., Jr., 1992. Oligocene-Pleistocene calcareous nannofossils from Southern Ocean sites 747, 748, and 751. *Proceedings of the Ocean Drilling Program, Scientific Results*, **120**, 509-522.
- Ziveri P., Thunnell R.C. & Rio R., 1995. Seasonal changes in coccolithophorid densities in the Southern California Bay during 1991-1992. *Deep Sea Research*, **42**, 1881-1903.
- Bicolumnus ovatus* Wei & Wise, 1990
- Chiasmolithus altus* Bukry & Percival, 1971
- Dictyococcites bisectus* Hay Mohler & Wade, 1966
- Dictyococcites hesslandii* (Haq) Haq & Lohman, 1976
- Dictyococcites productus* (Kamptner) Backman, 1980
- Reticulofenestra daviesi* (Haq) Haq, 1970
- Reticulofenestra hampdenensis* Edwards, 1973
- Reticulofenestra minuta* Roth, 1970
- Reticulofenestra minutula* (Gartner) Haq & Berggren, 1978
- Reticulofenestra oamaruensis* (Deflandre) Stradner and 1968
- Reticulofenestra umbilicus* (Levin) Martini & Ritzkowski, 1968
- Sphenolithus moriformis* (Bronnimann & Stradner) Bramlette & Wilcoxon, 1967
- Thoracosphaera heimii* Kamptner, 1941
- Thoracosphaera saxea* Stradner, 1961

Appendix 1 - List of species mentioned in the text.