ELSEVIER

Marine Micropaleontology 40 (2000) 403–416

MARINE MICROPALEONTOLOGY

www.elsevier.nl/locate/marmicro

Subtropical Front fluctuations south of Australia (45°09′S, 146°17′E) for the last 130 ka years based on calcareous nannoplankton

C.S. Findlay[a,*], J.A. Flores[b]

[a]Institute of Antarctic and Southern Ocean Studies, University of Tasmania, GPO Box 252-77, Hobart 7001, Australia
[b]Universidad de Salamanca, Departamento de Geología, 37008 Salamanca, Spain

Received 30 November 1999; accepted 30 May 2000

Abstract

Calcareous nannoplankton assemblages from a Late Quaternary deep-sea core (GC07; 46°09′S, 146°17′E) south of Australia provide information on regional palaeoceanography and palaeoclimate changes in the Southern Ocean, in particular the movement of the Subtropical Front for the past 130 ka years. Marine Isotope Stages 1–5 are identified through changes in calcareous nannoplankton assemblages, supported by ^{14}C dates, and oxygen isotope and %CaCO data.

Two distinct assemblages are recognised: a warm water assemblage with higher abundances of *Calcidiscus leptoporus*, *Emiliania huxleyi*, *Helicosphaera.carteri*, *Syracosphaera pulchra*, *Gephyrocapsa caribbeanica* and *Gephyrocapsa oceanica*; and, a cold water assemblage with higher abundances of *Gephyrocapsa muellerae* and *Coccolithus pelagicus*. Alternation between these two assemblages downcore in GC07 reflect movement of the Subtropical Front across the location and can be correlated to Marine Isotope Stages (MIS) 1–5. Sediments with a cold water assemblage indicate the position of the Subtropical Front equatorward of the site when transitional to sub-antarctic waters were overlying the site. Conversely sediments with a warm water assemblage indicate the Subtropical Front was poleward of GC07 when warmer, subtropical waters were over the site. MIS 1 and 5 are interpreted as warmer than MIS 3 (based on species composition) with the Subtropical Front more poleward than for MIS 3. During MIS 3 the Subtropical Front is interpreted as adjacent to or immediately poleward of GC07. Some species including *C. leptoporus* and *C. pelagicus* show negative covariance and are considered to be reliable species in identifying glacial and interglacial intervals in this region.

Comparison with established biostratigraphy based on calcareous nannoplankton showed the datum event for the reversal between *E. huxleyi* and *G. muellerae* of 73 ka in transitional waters is not applicable in this region. The reversal between these two species occurs between 48 and 30 cm downcore in GC07 with a ^{14}C date of 11 020 year BP at 49–48 cm, i.e. the reversal event is younger than this date. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: calcareous nannoplankton; palaeoceanography; palaeoclimate; biostratigraphy; Southern Ocean

1. Introduction

The Southern Ocean plays a major role in global deep ocean circulation and has been identified as leading the northern hemisphere in sea surface temperature changes during glacial terminations (Labracherie et al., 1989; Howard and Prell, 1992, 1994; Labeyrie et al., 1996). Calcareous nannoplankton, which reflect the signatures of surface waters, are an ideal proxy for

---

* Corresponding author.
E-mail address: claire_findlay@hotmail.com (C.S. Findlay).

0377-8398/00/$ - see front matter © 2000 Elsevier Science B.V. All rights reserved.
PII: S0377-8398(00)00045-1

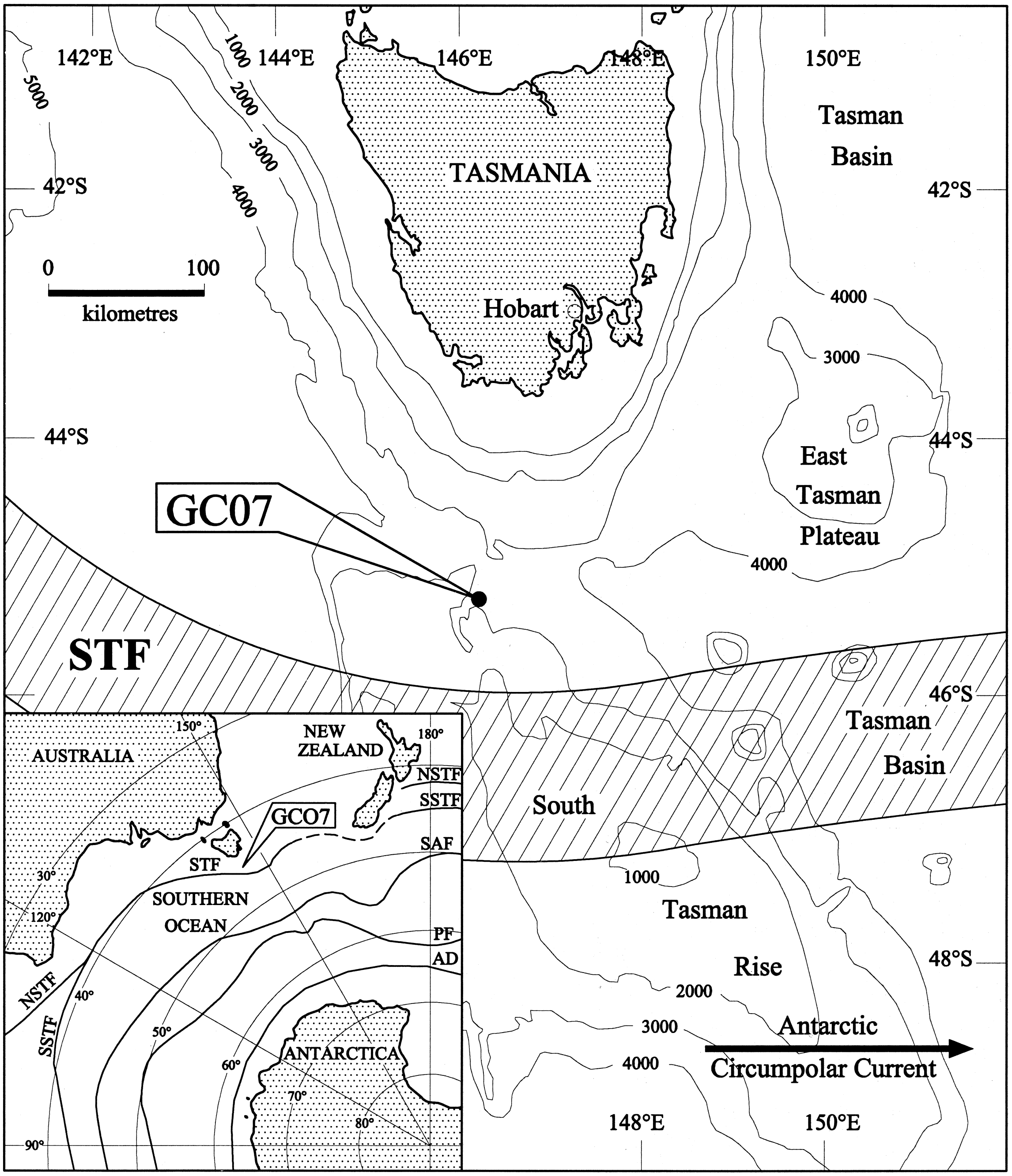

Fig. 1. Location of gravity core GC07 (45°09′S, 146°17′E) on the South Tasman Rise.

Table 1
Core depths of ^{14}C dates and estimated sedimentation rates for core GC07

Core depth (cm)	Age of oxygen isotope stages (ka) (Martinson et al., 1987)	^{14}C dates corrected for reservoir effect (years BP)	Estimated sedimentation rate (cm/ka)
0–3		1167	
48.5		11 020	4.9
57.5		11 420	7
70	Stage 2 (12.05)		120
82		14 880	28
120	Stage 3 (24.11)		13
270	Stage 4 (58.96)		7.9

the study of palaeoceanography and palaeoclimate in the Southern Ocean. In addition, preservation of calcium carbonate sediments provides a record of geochemical (calcium and carbon dioxide) pathways. Calcareous nannoplankton are important in palaeoceanography as they are often the major component of calcium carbonate sediments.

Studies of Quaternary palaeoceanography based on calcareous nannofossils is limited in the southern hemisphere (Geitzenauer, 1969, 1972; Gard, 1989; Gard and Crux, 1991; Wells and Okada, 1996, 1997; Wells and Connell, 1996; Hiramatsu and De Deckker 1997; Flores et al., 1999) in comparison to the northern hemisphere (Gard, 1989; Gard and Backman, 1990; Kleijne, 1991; Baumann and Matthiesen, 1992; Samtleben and Schröder, 1992; Samtleben et al., 1995a, b; Knappertsbuch and Brummer, 1995). This study provides additional information for the southern hemisphere in this area of research.

The objectives of this study are two-fold, firstly to examine palaeoceanography in the Southern Ocean based on calcareous nannoplankton data including the identification of glacial and interglacial intervals; movement of the Subtropical Front (STF); and, the relationship between palaeoclimate and changes within the nannofossil assemblage. The results show movement of the STF is in agreement with previous studies in the southern hemisphere based on faunal migrations of planktonic foraminifera (Howard and Prell, 1992) and radiolarian assemblages (Morley, 1989) although this disagrees with others (Wells and Connell, 1996). Secondly, to compare the Quaternary biostratigraphy based on calcareous nannoplankton in this region with the established biostratigraphy for this group of microfossils. Results show the datum event identified as the reversal between *Emiliania huxleyi* and *Gephyrocapsa muellerae* differs in this region in comparison to the established record (Thierstein et al., 1977).

2. Materials and techniques

During the Australian Geological Survey Cruise RS 147 (Exon et al., 1995) to the South Tasman Rise, an initial sampling of eighteen gravity coretops from the South Tasman Rise identified four with a Holocene age (Connell and Sikes, 1997). Of these, core GC07 was selected on the basis of its proximity to the STF, surface sediments of Holocene age, subsequent ^{14}C dates (Samson, 1998) (Table 1) and minimal reworking within the core. GC07, a 5.3 m gravity core, was collected from a depth of 3307 m south of Australia at 45°09′S, 146°17′E (Fig. 1, map). The location of GC07 is equatorward of the STF as identified by Belkin and Gordon (1996) and Rintoul et al. (1997).

Downcore sediment samples were taken immediately after the core arrived on board at 10 cm intervals between the coretop, and 200 and 20 cm intervals from 210 cm to the base of the core (510 cm). Samples were placed in plastic vials and subsequently oven-dried at 60°C in the same vials.

Examination and counting of each sample was carried out using a light microscope (LM) and a scanning electron microscope (SEM). Preparation for the LM involved mixing a small amount of sediment

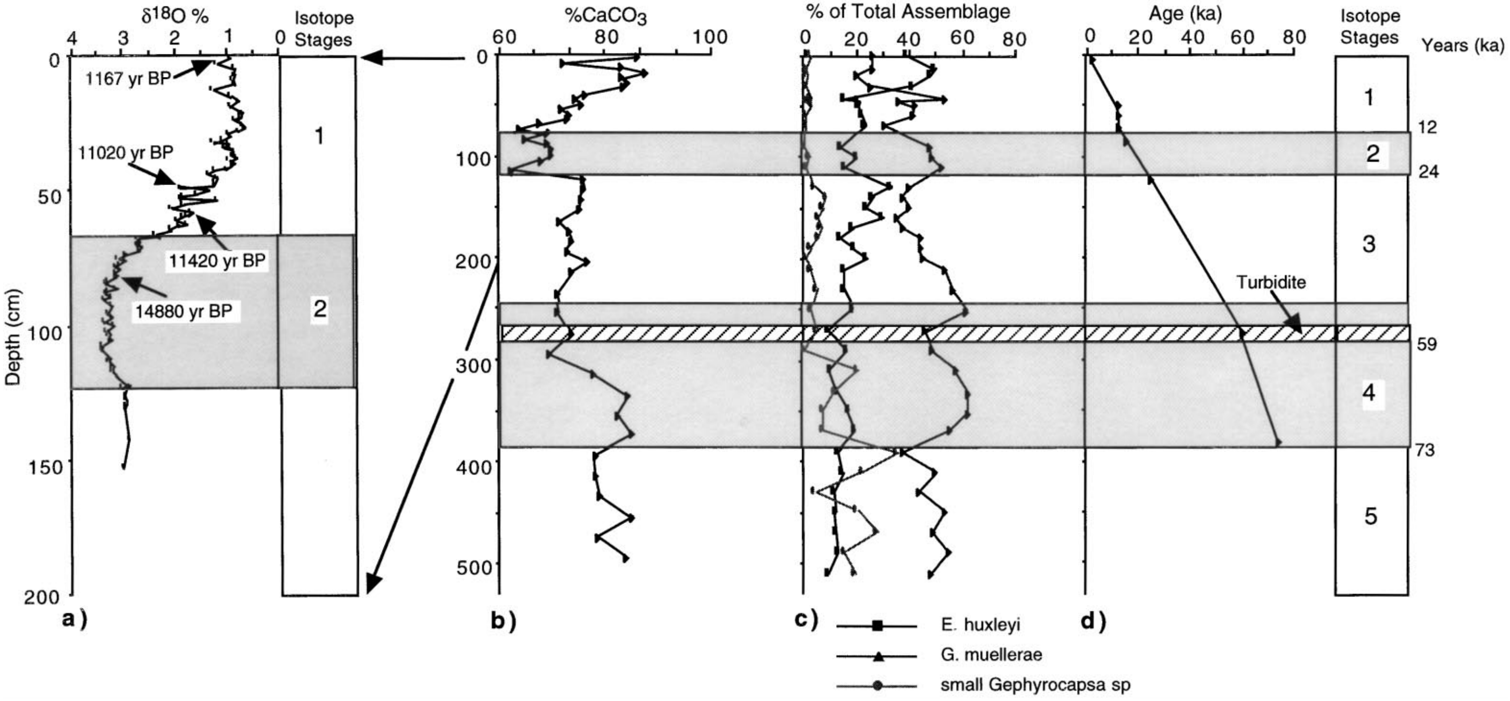

Fig. 2. Stratigraphy for GC07: (a) oxygen isotope data and ^{14}C dates from Samson (1998); (b) %CaCO$_3$ curve (McCorkle unpublished; Connell and Sikes, 1997); (c) percentages of stratigraphically significant species; (d) estimated sedimentation rate based on dates of oxygen isotope stages of Martinson et al. (1987) and ^{14}C dates.

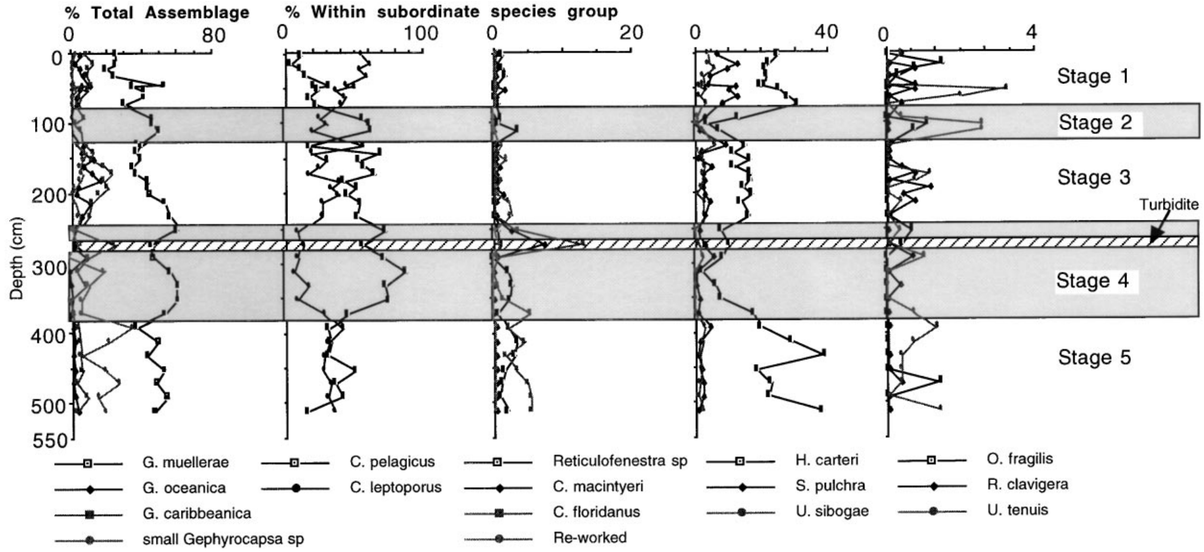

Fig. 3. Percentages of calcareous nannoplankton species for core GC07. 'Reworked (others)' includes cf. *Reticulofenestra* sp., *Sphenolithus* sp. and *Discoaster* sp. Ages of isotopic events are based on Martinson et al. (1987).

directly onto a glass slide with buffered distilled water. This slurry was spread thinly over the slide and dried on a hotplate to prevent coagulation. When dry a cover slip was mounted using an ultraviolet light sensitive compound fixed under ultraviolet light for approximately 15 min. The samples contained few clay particles eliminating the need for ultrasonification, addition of anti-flocculants or centrifuging. Preparation for SEM slides followed the same procedure substituting mica slides for glass slides.

The counting procedure follows Okada (1992). Two counts of minimum 300 coccoliths were made for each sample. The first count included percentages of the total assemblage for *E. huxleyi*, individual *Gephyrocapsa* species and the single category 'subordinate species', i.e. the sum of all other species as a single percentage of the total assemblage. The second count was restricted to percentages of individual species within the 'subordinate species' group, i.e. excluding *E. huxleyi* and gephyrocapsids. This method overcomes the bias of a few species dominating the assemblage. Examination and counting for each sample was carried out using a Zeiss Axioskop LM with an oil immersion objective of 100 × with a total magnification of 1000 ×. Supplementary examinations of samples were made with a JEOL SEM.

3. Oceanographic setting

The South Tasman Rise is the southern extension of the continental margin of Australia and lies between water depths of 1000–4000 m (Exon et al., 1995). The plateau is continuously swept by strong east-flowing currents associated with the intensification of the Antarctic Circumpolar Current in this region (Callahan, 1971). Evidence of strong current activity is reflected by erosion with many coretops in the region found to be Late Pleistocene or older (Osborn et al., 1983; Belford 1989; Wells and Connell, 1996). In contrast, core GC07 of this study has a Holocene coretop. The location of GC07 on the northeast slope of the plateau may provide protection from the east-flowing currents preserving younger sediments in this region. The water depth of 3307 m for core GC07 is well above the established depths for the calcite lysocline in the southern high latitudes (Constans, 1975; Kolla et al., 1976; Takahashi et al., 1981; Howard and Prell, 1994.) suggesting good preservation of carbonate sediments at this location.

Three major oceanic fronts are located south of Australia (Belkin and Gordon, 1996). In a poleward direction they are the STF at approximately 45–46°S, defined by 12°C isotherm at 150 m; the Subantarctic Front, at approximately 50–52°S, where the largest horizontal gradient between 3–8°C occurs at 300 m; and, the Polar Front at approximately 63°S, where the isotherms dome. Core GC07 is located equatorward of the STF in the present-day subtropical zone.

4. Stratigraphy

Stratigraphy of core GC07 is based on changes in calcareous nannoplankton assemblages combined with %$CaCO_3$ data (McCorkle, unpublished; Connell and Sikes, 1997) supplemented by $\delta^{18}O$ data and ^{14}C dates (Samson, 1998) for the upper 150 cm (Fig. 2). Marine Isotope Stages (MIS) 1–5 are recognised.

Emiliania huxleyi was identified in all samples to the base of core GC07 (Fig. 2) indicating an age younger than the first occurrence (FO) of *E. huxleyi*, i.e. late MIS 8 or younger (Thierstein et al., 1977; Weaver, 1993). This is supported by the absence of high abundances of *Gephyrocapsa caribbeanica*, associated with MIS 8–15 (Gard and Backman, 1990; Weaver, 1993). As MIS 7 and 6 are dominated by small *Gephyrocapsa* spp, the base of core GC07(dominated by *G. muellerae*) is MIS 5 or younger.

The presence of *E. huxleyi*, dominance of *G. muellerae* and increase in small *Gephyrocapsa* spp between 510 and 380 cm is interpreted as MIS 5. Similarly, higher abundances of small *Gephyrocapsa* species have been identified in MIS 5 (Gard and Backman 1990; Gard and Crux, 1991; Weaver, 1993; Jordan et al., 1996; Okada and Wells, 1997). The reduction of small *Gephyrocapsa* species, 390–370 cm, is interpreted as the boundary between MIS 5 and 4.

Identification of MIS 4 between 380 and 250 cm is based on the increase of *Coccolithus pelagicus* and *G. muellerae* (Fig. 3) considered to represent colder waters. Within this interval a peak of reworked species occurs at 270 cm corresponding to a turbidite structure identified in the core log. Between 230 and 130 cm the calcareous nannoplankton assemblage changes with higher abundances of species associated with warmer waters (*Calcidiscus leptoporus*, *Helicosphaera carteri*, *Syracosphaera pulchra*, *Gephyrocapsa caribbeanica* and *Gephyrocapsa oceanica*). This interval is interpreted as MIS 3 supported by the %$CaCO_3$ data, which records an increase for this interval from MIS 2. The interval at 120 cm was barren of coccoliths and may represent the onset of MIS 2.

Increases in *C. pelagicus* and *G. muellerae* at the depth of 110 to 70 cm indicate a cool interval, interpreted as MIS 2. This is supported by the oxygen isotope data (Samson, 1998), which shows higher values for the same interval compared to 70 cm and coretop; the ^{14}C date of 14 880 years BP at 82–83 cm; and lower %$CaCO_3$ values. Similarly, interpretation of MIS 1 between 70 cm and coretop based on increases in warm water species is supported by a decrease in oxygen isotope values; three ^{14}C dates (11 420 years BP at 58–57 cm, 11 020 years BP at 49–48 cm and 1167 years BP at 3–0 cm); and, an increase in %$CaCO_3$ values.

4.1. Reversal event between Gephyrocapsa muellerae *and* Emiliania huxleyi

Between 40 cm core depth and the coretop *E. huxleyi* dominates the assemblage. The reversal in dominance between *E. huxleyi* and *G. muellerae* has been established as a datum event at 85 ka (MIS 5) in tropical waters and 73 ka (MIS 4) in transitional waters (Thierstein et al., 1977). In this study the reversal is found between 40 and 30 cm core depth with a ^{14}C date of 11 020 years BP at 49–48 cm (Samson, 1998). The earlier date (less than 11 ka) for the reversal event between these two species is possible in this region. This datum event is time transgressive and has been documented at 40 ka in regions of coastal upwelling (Jordan et al., 1996), 73–47 ka in the western Mediterranean (Flores et al., 1997) and 42 ka in southeast Indonesian basins (Biekart, 1989). South of Australia the reversal between these two species was found between MIS 2 (~12 ka) and MIS 4 (Hiramatsu and De Deckker, 1997) and between 11–41 ka (Wells and Okada, 1996). Possibly this time transgressive event occurs at 11 ka in the high latitudes of the Southern Ocean. Alternatively, dissolution of calcareous nannoplankton in this region may obscure the datum event through the preferential preservation of the more robust *G. muellerae* over *E. huxleyi*. In either case the established datum event of 73 ka for the reversal between these two species is not applicable in the high latitudes of the Southern Ocean.

5. Preservation and reworking

The preservation of coccoliths in sediments of GC07 is moderate to good. Examples of dissolution are found on coccoliths of *E. huxleyi* where the "T" elements on the distal plate show various stages of reduction and in some cases are missing altogether. Some coccoliths of *G. muellerae* are represented without a central bridge structure. In contrast, the presence of more fragile species including *Umbellosphaera tenuis*, *Oolithus fragilis*, *Rhabdosphaera clavigera*, *Umbilicosphaera sibogae* and *S. pulchra* suggests that the dissolution is not severe.

The barren interval identified at 120 cm (early MIS 2) may be attributed to either a dissolution, non-depositional or erosional event at the onset of MIS 2. Intrusion of colder water at the site during this interval may have affected productivity or introduced carbonate depleted waters.

6. Calcareous nannoplankton

The two dominant species in GC07, *G. muellerae* and *E. huxleyi*, recorded percentages (of the total assemblage) between 34 and 62% and 8 and 32%, respectively, from the base of the core (510 cm) to 43 cm. From 30 cm to coretop percentages of 19 to 25% and 38 and 49%, respectively, were recorded. *G. muellerae* dominates all samples from the base of the core (510 cm) to 43 cm and *E. huxleyi* from 30 cm to the coretop. These two species alternate in abundance in MIS 1–4 (with the exception of 270 cm) and to some extent MIS 5.

Within the subordinate species group *C. pelagicus* (2 to 87% of the assemblage excluding *E. huxleyi* and gephyrsocapsids) and *C. leptoporus* (9 to 59%) dominate (Fig. 3). *C. leptoporus* dominates MIS 1 with abundance peaks in MIS 3 and 5. *C. pelagicus* dominates MIS 2–5 with highest abundances in MIS 2 and 4. Of the remaining subordinate species maximum percentages showed 39% for *H. carteri*, 13% for *S. pulchra* and 5% for *U. sibogae*. Maximum percentages for the remaining subordinate species *O. fragilis*, *R. clavigera* and *U. tenuis* are less than 2%.

The negative covariance pattern between *C. pelagicus* and *C. leptoporus* can be correlated to episodes of cold and warm water intervals, where higher abundances of *C. pelagicus* represent cold water intervals (MIS 2 and 4). Peaks of *G. muellerae* are recorded for the same intervals and the two species combined are interpreted as a cold water assemblage. Conversely, peaks of *C. leptoporus* in MIS 1 and 3 correlate to abundance peaks for *E. huxleyi*, *H. carteri*, *S. pulchra*, *G. oceanica* and *G. caribbeanica*, interpreted as a warm water assemblage. This pattern is not so clear in MIS 5.

Low percentages of some subordinate and reworked species preclude their use as reliable proxies for palaeoceanographic interpretations on an individual basis, although, combined with other data are considered useful; e.g., peak of reworked species indicates erosional event. *Florisphaera profunda* is present in some samples though extremely rare and is not included in the data set other than to note here its occasional presence. This species is associated with tropical and subtropical waters and is at the limit of its biogeographic range at the location of GC07, which lies between the subtropical and transitional zones.

7. Discussion

7.1. Stratigraphy

Interpretation of MIS 5 and 4, based on changes within the calcareous nannoplankton assemblages, remains tentative without further supporting data. The peaks of small *Gephyrocapsa* spp between 510 and 390 cm may reflect substages of MIS 5 similar to those identified elsewhere (Gard, 1989; Weaver and Thomson, 1993; Jordan et al., 1996; Flores et al., 1997) with the highest percentage at 390 cm representing MIS 5a. Similarly, MIS 3 is identified (230–130 cm) by changes in the assemblage. However, increasing %$CaCO_3$ downcore from 120 cm supports this interpretation. The interpretation of MIS 2 and 1 can be approached with confidence based on nannoplankton assemblages coupled with %$CaCO_3$, ^{14}C dates and $\delta^{18}O$ data.

The lower than expected percentages of *E. huxleyi* (<50%) for MIS 1 within the *E. huxleyi* acme may be the result of dissolution. If so, the preferential preservation of *G. muellerae* over *E. huxleyi* may obscure the 73 ka date for the reversal between these two species in this region. The effects of dissolution may also lead to difficulties distinguishing *E. huxleyi* coccoliths without “T” elements from *G. muellerae* coccoliths without central bridge structures using a light microscope. In this study the use of a scanning electron microscope overcomes this problem. Changes in productivity may reduce the abundance of *E. huxleyi* in the sediments. Research on living assemblages in the same region (Findlay, 1998; Findlay and Giraudeau, submitted for publication) show a significant drop in productivity poleward across the STF.

7.2. Preservation and reworking

The virtual absence of *F. profunda* coupled with structural changes to individual coccoliths suggests that the effects of dissolution are significant in preservation of calcium carbonate in this region. Although the lysocline is approximately 3307 m for this region (Constans, 1975; Kolla et al., 1976; Takahashi et al. 1981; Howard and Prell, 1994) the site is affected by the Circumpolar Deep Water (CDW) associated with increased CO_2, which would account for dissolution. The CDW has been identified at depths between 1600 and 4000 m in this region (Passlow et al., 1997). In contrast the presence of species identified as less resistant (McIntyre and McIntyre, 1971; Berger, 1973) indicates that the dissolution is not significant; however, the solution indices previously recorded may not be applicable in this region.

Interpretation of the barren interval at 120 cm is problematic. Similar barren intervals in sediments above the CCD in the southern hemisphere have been interpreted as movement of the PF equatorward of those sites for those intervals (McIntyre et al., 1970; Gard, 1989) as coccosphere production is limited poleward by the PF (McIntyre et al., 1972; Nishida, 1986; Findlay, 1998; Findlay and Giraudeau, 2000). In this event a migration of the PF by 8° equatorward from its present-day location in early MIS 2 would be required for the site of GC07, an unlikely scenario. Although the PF has been placed at 45°S at the Last Glacial Maximum in the southeastern Indian Ocean based on faunal migrations (Morley, 1989), the poleward displacement of fronts south of Tasmania resulting from ocean-floor topography precludes a similar interpretation for GC07. In addition, the presence of more fragile species (*U. tenuis*, *U. sibogae*, *O. fragilis*, *R. clavigera* and *S. pulchra*) in all other samples for MIS 2 suggests the absence of polar waters during this interval.

The barren interval in GC07 may be the result of a carbonate dissolution event similar to that identified in the South Atlantic during MIS 2 when the PF was poleward of the core site (Gard, 1989; Hays et al., 1976). Alternatively, it may be the product of an erosional event associated with the onset of MIS 2. Intensification of currents during glacial intervals resulted in greater erosion of bottom sediments. Earlier studies (Wells and Okada, 1996) to the northwest of GC07, adjacent to the south coast of Australia, recorded a major hiatus between the lower section of MIS 2 and MIS 10, suggesting a major erosional event during early MIS 2. The same erosional event could be reflected in GC07 at 120 cm depth.

Low abundances of reworked species including *Discoaster* sp., *Sphenolithus* sp., *C. floridanus, Calcidiscus macintyrei* and reticulofenestrids indicate minor reworking throughout the core (Fig. 3). In low abundances reworked species including *Pseudoemiliania lacunosa* (330, 470 and 510 cm) are not considered stratigraphically important. The peak of reworked species at 270 cm is associated with a turbidite feature recognisable in the core log. The peak of *Cyclicargolithus floridanus* within the turbidite suggests erosion of Miocene sediments upslope from GC07.

7.3. Palaeoceanographic implications from calcareous nannoplankton

Two separate assemblages of nannoplankton are identified in GC07. The first is identified by higher percentages of *C. pelagicus* and *G. muellerae* interpreted as a cold water assemblage. Previous research has identified *C. pelagicus* with cooler waters (McIntyre and Bé, 1967; Geitzenauer, 1972; Geitzenauer et al., 1976; Okada and McIntyre, 1977, 1979; Raffi and Rio, 1981; Samtleben and Schröder, 1992; Baumann, 1995) and higher percentages during glacial intervals in Quaternary cores from the southern hemisphere (Gard, 1989; Wells and Okada, 1996; Hiramatsu and De Deckker, 1997). *G. muellerae* has also been associated with colder waters (Winter et al., 1994; Samtleben et al., 1995a) recording higher percentages in cooler intervals from Late Quaternary cores in high latitudes both in the regional (Hiramatsu and De Deckker, 1997; Wells and Okada, 1997) and northeast Atlantic (Lototskaya et al., 1998) areas. Results from GC07 found higher abundances of this assemblage for the intervals MIS 2 and 4 (Fig. 3).

The warm water assemblage that records higher percentages of *C. leptoporus*, *H. carteri*, *S. pulchra* and *G. oceanica* is associated with MIS 1, 3 and 5 in GC07. Highest percentages of *C. leptoporus* and *S. pulchra* were recorded for MIS 1 with highest percentages of *H. carteri* recorded in MIS 5 (Fig. 3). These species have been identified as warm water species (McIntyre and Bé, 1967; McIntyre et al., 1970; Samtleben et al., 1995a;) and associated previously with interglacial intervals in the southern hemisphere (Geitzenauer, 1969, 1972; Gard, 1989; Wells and Okada 1997; Hiramatsu and De Deckker, 1997).

The resulting negative covariance between *C. leptoporus* and *C. pelagicus* in GC07 can be used to interpret palaeoceanography in this region, confirmed by previous studies (Geitzenauer, 1969; Gard, 1989; Wells and Okada, 1996). For the interval MIS 5 the pattern is not so clear, possibly the result of cyclical environmental changes associated with substages of MIS 5. The reduced abundance in late MIS 5 in GC07 indicates a warmer interval than for the remainder of MIS 5. In the North Atlantic *C. pelagicus* is sparse or absent during MIS 5, interpreted as an interval too warm for this species (Baumann, 1995). Living assemblages in high latitudes of the northern hemisphere show *C. pelagicus* occupies the transitional waters where small changes in environmental parameters would affect their production (Geitzenauer, 1972). In the southern hemisphere this has not always been present (McIntyre et al., 1970) and was possibly absent in late MIS 5. Reversal in dominance between *C. pelagicus* and *C. leptoporus* in early MIS 1 (70 cm) of GC07 suggests a similar event, i.e. the absence of a transitional zone through the poleward movement of the STF, resulting in the replacement of *C. pelagicus* by *C. leptoporus* in the Southern Ocean (McIntyre and Bé, 1967; McIntyre et al., 1970; Geitzenauer, 1972).

Increases of small *Gephyrocapsa* spp in late MIS 5 (MIS 5a) are in contrast to previous results from this region (Wells and Okada, 1997; Hiramatsu and De Deckker, 1997), which recorded highest percentages in MIS 5e. However, it is possible the base of GC07 is no older than MIS 5d. Data from NW Africa (Jordan et al., 1996) and the northeast Atlantic (Lototskaya et al., 1998) record small *Gephyrocapsa* spp dominant over *G. muellerae* in MIS 5 interpreted as warmer waters for this interval in those regions. The negative covariance in GC07 between *G. muellerae* and small *Gephyrocapsa* spp, noted in previous studies (Geitzenauer et al., 1976; Flores et al., 1997; Lototskaya et al., 1998) confirms the palaeoceanographic interpretation for this region.

Increases of *G. oceanica* in MIS 1 and 3 reflect this species preference for warmer waters. However, combined with its possible environment and evolutionary changes this species is not considered to be a reliable palaeoclimatic indicator in this region. In addition, abundance variations of *G. oceanica* have been associated with factors other than temperature (Knappertsbusch, 1993).

7.4. Palaeoceanography

The position of the STF is interpreted as poleward of GC07 during MIS 1 and 5 when warmer, subtropical waters covered the site. This is reflected by higher productivity including increased abundance of *C. leptoporus*, *G. oceanica*, *H. carteri*, *S. pulchra*, *O. fragilis* and *U. tenuis*. Similar conditions are found at present where the STF (separating subtropical waters from subantarctic waters) is poleward of GC07, the overlying waters are subtropical and the living assemblage reflects these conditions (Nishida, 1986; Findlay, 1998; Findlay and Giraudeau, 2000).

Increase of productivity in early MIS 1 reflected by a high sedimentation rate (Fig. 2d), higher %$CaCO_3$ and higher abundances of warm water species is interpreted as a more equatorward position of the STF than the present-day. Increases in %$CaCO_3$ have been used to infer high productivity during interglacial intervals in the Southern Ocean (Howard and Prell, 1994). However, as MIS 4 records relative high %$CaCO_3$, the latter cannot be reliable as a proxy for glacial and interglacial intervals without further substantive data. This is further supported by the results of Gard and Crux (1991) who identified intervals barren of coccoliths and rich in %$CaCO_3$ in the Southern Ocean (Gard and Crux, 1991).

The interpretation for the position of STF in MIS 1 is supported by previous studies in the southern hemisphere (Morley, 1989; Howard and Prell, 1992). Although, one study suggests the STF was equatorward of its present day position in early MIS 1 through to 10 ka when it moved poleward to its present-day position (Wells and Connell, 1996). However, these authors note the δ^{18}O and palaeotemperature record may be distorted due to disturbances and hiatuses within the cores.

For the interval MIS 3 lower percentages of warm water species coupled with an increase of *G. caribbeanica*, considered to represent cooler waters (Geitzenauer, 1969; Wells and Okada, 1996), indicates this interglacial was cooler than MIS 1 and 5, possibly with lower productivity. The position of the STF although equatorward of the present-day position, is interpreted as adjacent to or immediately poleward of GC07 for this interval. There is some evidence for fluctuation of the STF across the site during MIS 3, e.g., at 130 and 180 cm negative covariance between *C. pelagicus* and *C. leptoporus* may reflect poleward displacement of the STF. Conversely, the STF is interpreted as adjacent to or equatorward of GC07 during MIS 2 and 4 resulting in subantarctic waters over the site. These cooler intervals record less species diversity reflecting lower productivity for these intervals. Within MIS 5 a poleward shift in the position of the STF is identified between early MIS 5 and late MIS 5 based on the increase in productivity and abundance of warm water species, possibly to a position poleward of the present-day.

The barren interval recorded at 120 cm is interpreted as a dissolution event at the onset of MIS 2. The calcite lysocline in the southeast Indian Ocean has been documented as 600 m shallower than present-day in MIS 2 and 4 (Howard and Prell, 1994), which may account for this dissolution. Similarly, Passlow et al. (1997) identified dissolution in MIS 2 at a nearby location.

8. Conclusions

Two separate calcareous nannoplankton assemblages are identified in core GC07 south of Australia: a cold water assemblage with higher abundance of *G. muellerae* and *C. pelagicus* and a warm water assemblage with higher abundances of *C. leptoporus*, *H. carteri* and *S. pulchra*. Alternation of these two assemblages reflects movement of the STF over the location of GC07. Changes in the nannofossil assemblage can be correlated to MIS 1–5 supported by %$CaCO_3$, oxygen isotope data and ^{14}C dates. The position of the STF for these intervals is interpreted as poleward of its present-day position for early MIS 1 and MIS 5a. MIS 3 is considered to have been a cooler interglacial when the STF would have been equatorward of the position found in MIS 1 and 5 (although still poleward of GC07). Conversely the position of the STF for MIS 2 and 4 is interpreted as equatorward of GC07 site.

Palaeoceanographic interpretation based on species includes the negative covariance between *C. pelagicus* and *C. leptoporus*, which can be used as a reliable proxy for identifying glacial and interglacial intervals in this region. The reversal in dominance between these two species in MIS 1 indicates the disappearance of the transitional zone in the southern hemisphere leading to the disappearance of *C. pelagicus* in this region. Abundance peaks of other species including *H. carteri*, *S. pulchra* and small *Gephyrocapsa* spp can also be used as markers to identify palaeoclimatic changes in the subantarctic region, with increases of small *Gephyrocapsa* spp in MIS 5 a useful stratigraphic indicator. Productivity peaks occur during MIS 1, 3 and 5 but do not always correspond with higher percentages of %$CaCO_3$.

The biostratigraphic datum event of the reversal between *E. huxleyi*and *G. muellerae* is identified as younger than 11 ka in GC07. However, although this younger date is possible for this event in the high latitudes of the southern hemisphere, preferential dissolution of *E. huxleyi* obscuring the 73 ka datum event cannot be discounted. The barren sample at 120 cm may be the result of an erosional event in early MIS 2.

Acknowledgements

The authors would like to thank the Australian Geological Survey Organisation for participation in Cruise 147, Cath Samson for access to her data and John Cox for assistance with graphics. This research was supported by the Goddard Sapin-Jaloustre Scholarship Trust, the Bilateral Science and Technology Collaboration Program and the Coordinated

French–Australian Scientific Collaboration on the Environment.

Appendix A. Taxonomy

This taxonomic list includes all taxa identified in this study, following the descriptions and illustrations by Perch-Nielsen (1985) supplemented by Okada and McIntyre (1977), Takayama and Sato (1987), Wei and Thierstein (1991), Sato and Takayama (1992), Beaufort (1992) and Okada (1992). Species were identified using both a scanning electron microscope and light microscope. Species are listed in alphabetical order of Family name.

Four different species of gephyrocapsids were recognised, three with medium sized coccoliths and one with very small coccoliths. The three medium sized coccoliths are interpreted as: *G. caribbeanica*, with coccoliths between 3 and 6 μm and a closed or almost closed central area; *G. oceanica*, with coccoliths approximately 6μm and a bridge almost horizontal across the width of the central opening; and, *G. muellerae*, with coccoliths between 3 and 6 μm and a bridge spanning the central area at an oblique angle. The small *Gephyrocapsa* spp with coccoliths between 1 and 2.5 μm are not identified at species level.

The reticulofenestrids were categorised by three sizes: 6–12 μm with open (*R. pseudoumbilica*) and closed (*R. gelida*) central areas; 5–8 μm with open *R. minutula*) and closed or small (*R. productella* or *R. antarctica*) central areas; and 3–5 μm with a closed central area. These small species are considered to be end members of *R. productella* rather than *R. minuta* (<3 μm).

Although a ‘warm water’ and ‘cold water’ morphotype of *E. huxleyi* is observed in living assemblages of this region (Findlay, 1998; Nishida, 1986), only one morphotype is identified in the sediments of GC07. It is possible that the more fragile ‘warm water’ morphotype is subject to dissolution and not preserved, or, as the ‘warm water’ morphotype is at the limit of its range preservation in the sediments is diluted by the ‘cold water’ form.

A number of coccoliths were grouped together as ‘reworked spp’ and are considered to be mostly reticulofenestrids altered through mechanical breakage and dissolution precluding positive identification.

Family Ceratolithaceae Norris, 1965
Ceratolithus cristatus Kamptner, 1950 var. *cristatus*

Family Calciosoleniaceae Kamptner 1937
Calciosolenia murrayi Gran, 1912

Family Coccolithaceae Poche, 1913
Calcidiscus leptoporus (Murray and Blackman, 1898) Loeblich and Tappan, 1978 f. *leptoporus*
Calcidiscus macintyrei (Bukry and Bramlette, 1969) Loeblich and Tappan, 1978
Coccolithus pelagicus (Wallich, 1877) Schiller, 1930
Oolithus fragilis (Lohmann, 1912) Martini and Müller, 1972 var. *fragilis*
cf. Umbilicosphaera angustiforamen Okada and McIntyre 1977
Umbilicosphaera sibogae (Weber-Van Bosse, 1901) Gaarder, 1970 var. *sibogae*

Family Discoasteraceae Tan, 1927
Discoaster sp. Tan, 1927

Family Helicosphaeraceae Black, 1971, emend. Jafar and Martini, 1975
Helicosphaera carteri (Wallich, 1877) Kamptner, 1954 var. *carteri*
cf. *Helicosphaera sellii* Bukry and Bramlette, 1969

Family Noelaerhabdaceae Jerkovic, 1970
Cyclicargolithus floridanus (Roth and Hay in Hay et al., 1967) Bukry, 1971
Emiliania huxleyi (Lohmann, 1902) Hay and Mohler, in Hay et al., 1967 var. *huxleyi*
Gephyrocapsa caribbeanica Boudreaux and Hay, in Hay et al., 1967
Small *Gephyrocapsa* sp. cf. *G. ericsonii* McIntyre and Bé, 1967
Gephyrocapsa oceanica Kamptner, 1943
Gephyrocapsa muellerae Bréhéret, 1978
Pseudoemiliania lacunosa (Kamptner, 1963) Gartner, 1969

Reticulofenestra gelida (Geitzenauer, 1972) Backman, 1978
Reticulofenestra pseudoumbilica (Gartner, 1967) Gartner 1969
Reticulofenestra minutula (Gartner, 1967) Haq and Berggren, 1978
Small *Reticulofenestra* sp. cf. *Reticulofenestra productella* (Bukry 1973) Gallagher 1989 and *Reticulofenestra antarctica* Haq 1976

Family Pontosphaeraceae Lemmermann, 1908
Pontosphaera sp.

Family Rhabdosphaeraceae Ostenfeld, 1899
Acanthoica sp.
Rhabdosphaera clavigera Murray and Blackman, 1898, var. *clavigera*

Family Sphenolithaceae Deflandre, 1952
Sphenolithus sp.

Family Syracosphaeraceae Lemmermann, 1908
Syracosphaera pulchra Lohmann, 1902

Genera incertae sedis
Umbellosphaera tenuis (Kamptner, 1937) Paasche in Markali and Paasche, 1955

References

Baumann, K.-H., 1995. Morphometry of Quaternary *Coccolithus pelagicus* coccoliths from northern North Atlantic and its palaeoceanographical significance. In: Flores, J.A., Sierro, F.J. (Eds.), 5th INA Conference in Salamanca Proceedings, pp. 11–21.

Baumann, K.-H., Matthiesen, J., 1992. Variations in surface water mass conditions in the Norwegian Sea: evidence from Holocene coccolith and dinoflagellate cysts. Mar. Micropal. 20, 129–146.

Belford, D.J., 1989. Planktonic foraminifera and age of sediments, West Tasmanian margin, South Tasman Rise and Lord Howe Rise. BMR J. Aust. Geol. Geophys. 11, 37–62.

Belkin, I.M., Gordon, A.L., 1996. Southern Ocean Fronts from Greenwich Meridian to Tasmania. J. Geophys. 101 (C2), 3675–3696.

Berger, W.H., 1973. Deep-sea carbonates: evidence for a coccolith lysocline. Deep-Sea Res. 20, 917–920.

Biekart, J.W., 1989. The distribution of calcareous nannoplankton in Late Quaternary sediments collected by the Snellius II expedition in some southeast Indonesian basins. Palaentol. proc. B 92 (2 (June)).

Callahan, J.E., 1971. Velocity structure and flux of the Antarctic Circumpolar Current of South Australia. J. Geophys. Res. 76, 5859–5870.

Connell, R.D., Sikes, E.L., 1997. Controls on Late Quaternary sedimentation of the South Tasman Rise. Aust. J. Earth Sci. 44, 667–675.

Constans, R.E., 1975. A study of fluctuations in the carbonate compensation depth in the Southern Ocean south of Australia. MA thesis. Department of Geology, Florida State University.

Exon, N.F., Marshall, J.F., McCorkle, D.C., Alcock, M., Chaproniere, G.C.H., Connell, R., Dutton, S.J., Elmes, M., Findlay, C., Robertson, L., Rollet, N., Samson, C., Shafik, S., Whitmore, G.P., 1995. AGSO Cruise 147 Report — Tasman Rises Geological Sampling Cruise of Rig Seismic: Stratigraphy, Tectonic History and Palaeoclimate of the Offshore Tasmanian Region. Australian Geological Survey Organisation. Marine, Petroleum and Sedimentary Resources Program. Project 101.202. AGSO Record 1995/56.

Findlay, C.S., 1998. Living and Fossil Calcareous Nannoplankton from the Australian Sector of the Southern Ocean: Implications for Palaeoceanography. PhD thesis. University of Tasmania.

Findlay, C.S., Giraudeau, J., 2000. Extant calcareous nannoplankton in the Australian sector of the Southern Ocean caustral summers 1994 and 1995). Mar. Micropaleontol. 40, 415–437.

Flores, J.A., Sierro, F.J., Francés, G., Vazquez, A., Zamarreno, I., 1997. The last 100,000 years in the western Mediterranean: sea surface water and frontal dynamics as revealed by coccolithophores. Mar. Micropal. 29, 351–366.

Flores, J.A., Gersonde, R., Sierro, F.J., 1999. Pleistocene fluctuations of the Agulhas Current Retroflection based on the calcareous plankton record. Mar. Micropal. 37, 1–22.

Gard, G., 1989. Variations in coccolith assemblages during the last glacial cycle in the high and mid-latitude Atlantic and Indian Oceans. In: Crux, J.A., van Heck, S.E. (Eds.), Nannofossils and their Applications, Proceedings of the International Nannofossil Association Conference, London, 1987. The British Micropalaeontological Society / Ellis Horwood, Chichester, pp. 108–121.

Gard, G., Backman, J., 1990. Synthesis of Arctic and Sub-Arctic coccolith biochronology and history of North Atlantic drift water influx during the last 500,000 years. In: Bleil, U., Thiede, J. (Eds.), Geological History of the Polar Oceans: Arctic versus Antarctic. Kluwer Academic, Netherlands, pp. 417–436.

Gard, G., Crux, J.A., 1991. Preliminary results from Hole 704A: Arctic-Antarctic correlation through nannofossil biochronology. Proc. ODP Sci. Res., 114.

Geitzenauer, K.R., 1969. Coccoliths as Late Quaternary Palaeoclimatic indicators in the Subantarctic Pacific Ocean. Nature 223, 170–172.

Geitzenauer, K.R., 1972. The Pleistocene calcareous nannoplankton of the subantarctic Pacific Ocean. Deep Sea Res. 19, 45–60.

Geitzenauer, K.R., Roche, M.B., McIntyre, A., 1976. Modern Pacific coccolith assemblages: derivation and application to Late

Pleistocene palaeotemperature analysis. Geol. Soc. Am. Memoir 145, 423–448.

Hays, J.D., Imbrie, J., Shackleton, N.J., 1976. Variations in the earth's orbit: pacemaker of the Ice Ages. Science 194, 1121–1132.

Hiramatsu, C., De Deckker, P., 1997. The late Quaternary calcareous nanoplankton assemblages from three cores from the Tasman Sea. Palaeoceanog. Palaeoclim. Palaeoecol. 131, 391–412.

Howard, W.R., Prell, W.L., 1992. Late Quaternary surface circulation of the southern Indian Ocean and its relationship to orbital variations. Palaeoceanography 9 (3), 453–482.

Howard, W.R., Prell, W.L., 1994. Late Quaternary $CaCO_3$ production and preservation in the Southern Ocean: implications for oceanic and atmospheric carbon cycling. Palaeoceanography 9 (3), 453–482.

Jordan, R.W., Zhao, M., Eglinton, G., Weaver, P.P.E., 1996. Coccolith and alkenone stratigraphy at a NW Africa upwelling site (ODP 658C) over the last 130,000 years. In: Moguilevsky, A., Whatley, R. (Eds.), Microfossils and Oceanic Environments. University of Wales Aberystwyth Press, pp. 11–130.

Kleijne, A., 1991. Holococolithophorids from the Indian Ocean, Red Sea, Mediterranean Sea and North Atlantic Ocean. Mar. Micropal. 17, 1–76.

Knappertsbusch, M., 1993. Living and Holocene coccolithophores: Mediterranean Sea. Mar. Micropal. 21 (1-3), 219–247.

Knappertsbuch, M., Brummer, G.-J.A., 1995. A sediment trap investigation of sinking coccolithophorids in the North Atlantic. Deep Sea Res. 42 (7), 1083–1109.

Kolla, V., Bé, A.W.H., Biscaye, P.E., 1976. Calcium Carbonate distribution in the Surface Sediments of the Indian Ocean. J. Geophys. Res. 81 (15), 2605–2616.

Lototskaya, A., Ziveri, P., Ganssen, G.M., van Hinte, J.E., 1998. Calcareous nannofloral response to Termination II at 45°N, 25°W (northeast Atlantic). Mar. Micropal. 34, 47–70.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0–30,000-year chronostratigraphy. Quat. Res. 27, 1–29.

McIntyre, A., Bé, A.W.H., 1967. Modern coccolithophoridae of the Atlantic Ocean I. Placoliths and cyrtoliths. Deep Sea Res. 14, 561–597.

McIntyre, A., Bé, A.W.H., Roche, M.B., 1970. Modern Pacific coccolithophorida: a palaeontological thermometer. N.Y. Acad. Sci. Trans. 32 (6), 720–731 (series II).

McIntyre, A., McIntyre, R., 1971. Coccolith concentrations and differential solution in sediments. In: Funnel, B.M., Riedel, W.R. (Eds.), The Micropalaeontology of Oceans, pp. 253–261 (chap. 16).

McIntyre, A., Ruddiman, W.F., Jantzen, R., 1972. Southward penetrations of the North Atlantic Polar Front: faunal and floral evidence of large-scale surface water mass movements over the last 225,000 years. Deep Sea Res. 19, 61–77.

Morley, J.J., 1989. Variations in the high-latitude oceanographic fronts in the southern Indian Ocean: an estimation based on faunal changes. Palaeoceanography 4 (5), 547–554.

Nishida, S., 1986. Nannoplankton flora in the Southern Ocean, with special reference to siliceous varieties. Mem. Nat. Instit. Polar Res. 40, 56–68 special issue.

Okada, H., 1992. Biogeographic Control of Modern Nannofossil Assemblages in Surface Sediments of Ise Bay, Mikawa Bay and Kumano-Nada, off Coast of Central Japan. Mem. Sci. Geol., Mem. Ist. Geol. Mineral., Univ. Padova 43, 431–449.

Okada, H., McIntyre, A., 1977. Modern Coccolithophores of the Pacific and North Atlantic Oceans. Micropalaentology 23 (1), 1–55.

Okada, H., McIntyre, A., 1979. Seasonal distribution of modern coccolithophores in the western North Atlantic Ocean. Mar. Biol. 54, 319–328.

Okada, H., Wells, P., 1997. Late Quaternary nannofossil indicators of climate change in two deep-sea cores associated with the Leeuwin Current off Western Australia. Palaeoceanog. Palaeoclim. Palaeoecol. 131, 412–413.

Osborn, N.I., Ciesielski, P.F., Ledbetter, M.T., 1983. Disconformities and palaeoceanography in the southeast Indian Ocean during the past 5.3 million years. Bull. Geol. Soc. Am. 94, 1345–1358.

Passlow, V., Pinxian, W., Chivas, A.R., 1997. Late Quaternary palaeoceanography near Tasmania, southern Australia. Palaeoceanog. Palaeoclim. Palaeoecol. 131, 412–413.

Raffi, I., Rio, D., 1981. Coccolithus pelagicus (Wallich) a palaeotemperature indicator in late Pliocene Mediterranean deep sea record. In: Wezel F.C. (Ed.), Sedimentary basins of Mediterranean margins. C.N.R. Italian Project of Oceanography. Tecnoprint. pp. 187–190.

Rintoul, S.R., Donguy, J.R., Roemmich, D.H., 1997. Seasonal evolution of upper ocean thermal structure between Tasmania and Antarctica. Deep Sea Res. 44 (7), 1185–1202.

Samson, C., 1998. High resolution deglaciation records from the subtropical and subpolar southwest Pacific: implications for driving forces of climate. PhD thesis (unpub). University of Tasmania.

Samtleben, C., Schröder, A., 1992. Living coccolithophore communities in the Norwegian-Greenland Sea and their record in sediments. Mar. Micropal. 19, 33–354.

Samtleben, C., Baumann, C., Schröder-Ritzrau, A., 1995a. Distribution, composition and seasonal variation of coccolithophore communities in the northern North Atlantic. In: Flores, J.A., Sierro, F.J. (Eds.), 5th INA Conference in Salamanca Proceedings, pp. 219–235.

Samtleben, C., Schafer, P., Andruleit, H., Baumann, A., Baumann, K.-H., Kohly, A., Matthiessen, J., Schröder-Ritzrau, A., 1995b. Plankton in the Norwegian-Greenland Sea: from living communities to sediment assemblages — an actualistic approach. Geol. Rundsch. 84, 108–136 (Synpal Working Group; Springer).

Takahashi, T., Broecker, W.S., Bainbridge, W., 1981. The alkalinity and total carbon dioxide concentration in the world oceans. In: Bolin, B. (Ed.), Carbon Cycle Modelling, SCOPE. Wiley, New York, pp. 271–286.

Thierstein, H.R., Geitzenauer, K.R., Molfino, B., Shackleton, N.J., 1977. Global synchroneity of late Quaternary coccolith datum levels: validation by oxygen isotopes. Geology 5, 400–404.

Weaver, P.P.E., 1993. High resolution stratigraphy of marine

Quaternary sequences. In: Hailwood, E.A., Kidd, R.B. (Eds.), High Resolution Stratigraphy, 70. Geological Society, pp. 137–153 (special publication).

Weaver, P.P.E., Thomson, J., 1993. Calculating erosion by deep-sea turbidity currents during initiation and flow. Nature 364, 136–138.

Wells, P.E., Connell, R., 1996. Movement of hydrological fronts and widespread erosional events in the southwestern Tasmanian Sea during the Late Quaternary. Aust. J. Earth Sci. 44, 105–112.

Wells, P., Okada, H., 1996. Holocene and Pleistocene glacial palaeoceanography off southeastern Australia, based on foraminifers and nannofossils in Vema cored hole V18-222. Aust. J. Earth Sci. 43, 509–523.

Wells, P., Okada, H., 1997. Response of nannoplankton to major changes in sea-surface temperature and movements of hydrological fronts over Site DSDP 594 (south Chatham Rise, southeastern New Zealand), during the last 130 kyr. Mar. Micropal. 32, 341–363.

Winter, A., Jordan, R.W., Roth, P.H., 1994. Biogeography of living coccolithophores in ocean waters. In: Winter, A., Siesser, W. (Eds.), Coccolithophores. Cambridge University Press, pp. 161–178.