

Deglacial ocean and climate seasonality in laminated diatom sediments, Mac.Robertson Shelf, Antarctica

C.E. Stickley^a, J. Pike^{a,*}, A. Leventer^b, R. Dunbar^c, E.W. Domack^d,
S. Brachfeld^e, P. Manley^f, C. McClennan^b

^a*School of Earth, Ocean and Planetary Sciences, Cardiff University, Park Place, Cardiff, CF10 3YE, UK*

^b*Geology Department, Colgate University, 13 Oak Drive, Hamilton, NY 13346, USA*

^c*Department of Geological and Environmental Sciences, 325 Braun Hall, Stanford University, Stanford, CA 94305, USA*

^d*Geology Department, Hamilton College, 198 College Hill Road, Clinton, NY 13323, USA*

^e*Department of Earth and Environmental Studies, Montclair State University, Upper Montclair, NJ 07043, USA*

^f*Geology Department, Middlebury College, Middlebury, VT 05753, USA*

Received 1 October 2004; received in revised form 9 May 2005; accepted 23 May 2005

Abstract

The palaeoceanography and climate history of the East Antarctic Margin (EAM) are less well understood than those of West Antarctica. Yet, the EAM plays an important role in deep ocean circulation and the global ocean system and has likely done so in the past. Deglacial-age marine sediments from the EAM provide clues about its past role during this critical period of rapid climate change. Several deep basins across the EAM such as Iceberg Alley (~67°S, 63°E) on the Mac.Robertson Shelf (MRS) accommodate thick marine sequences that archive the deglaciation in the form of diatom-rich, continuously laminated (varved) sediments. These laminated sediments are pristinely preserved and contain seasonal and long-term information on the cryospheric and palaeoceanographic changes associated with the rapid retreat of the glacial ice sheet across the MRS. We present results of microfabric analysis of the lower ~2 m of deglacial varves from jumbo piston core JPC43B (Iceberg Alley). Backscattered electron imagery (BSEI) of polished thin sections and scanning electron microscope secondary electron imagery (SEI) of lamina-parallel fracture surfaces are used to analyze the varves. One hundred and ninety-two laminations are investigated and their nature and temporal significance are discussed in terms of seasonal deposition and cyclicity of diatom species. Our high-resolution palaeodata record exceptionally high diatom production and silica flux associated with the retreat of the East Antarctic Ice Sheet, and seasonal sea-ice changes along the EAM. This information is invaluable for assessing cryospheric-oceanographic variation and, therefore, the local and regional response to this period of rapid climate change. Varves are made up of lamina couplets comprising (i) thickly laminated to thinly bedded orange/orange-brown very pure diatom ooze dominated by *Hyalochoete Chaetoceros* spp. vegetative cells and resting spores, and (ii) brown/blue-grey terrigenous angular quartz sand, silt and clay with an abundant mixed diatom flora. The colour variation between these two types of lamination is striking. Using floristic and textural information we interpret the diatom oozes as spring flux and the terrigenous laminae as summer flux. Each couplet pair represents one annual cycle and reflects seasonal changes in nutrient availability and

* Corresponding author.

E-mail address: pikej@cf.ac.uk (J. Pike).

stratification associated with the cyclical advance and retreat of seasonal sea-ice. The diatom oozes can reach up to ~7.5 cm in thickness indicating enormous silica flux to the sea floor associated with ice sheet retreat.

© 2005 Elsevier B.V. All rights reserved.

Keywords: Deglaciation; Diatoms; East Antarctic Margin; Marine varves; Sea-ice; Seasonality

1. Introduction

Ice-cores and ocean sediments archiving the last deglaciation provide intriguing insights into the timing and nature of this rapid climate transition from the last glacial to the present interglacial (e.g., Duplessy et al., 1981, 1986; Mix and Ruddiman, 1985; Blunier et al., 1998; Petit et al., 1999; Bennett et al., 2000; Jouzel et al., 2001; Morgan et al., 2002; Shemesh et al., 2002). A clear understanding of the natural processes and responses involved in the step-wise, rapid switch from one climate state to the other is of prime interest (e.g., Broecker and Denton, 1989; Renssen et al., 2001). Although there is still some debate, it is apparent that the Southern Ocean (and, therefore, Antarctica) may have been influential in the Northern Hemisphere deglacial climate system (e.g., Broecker, 1998). For example, 3-dimensional ocean circulation models indicate that mass transport of relatively warm Southern Ocean waters into the Atlantic during the last two deglacial periods may have abruptly ‘kick started’ the Atlantic thermohaline circulation out of a weak glacial mode and into a strong interglacial mode (Knorr and Lohmann, 2003). However, reliable field data necessary for addressing these past interhemispheric phase relationships and teleconnections are only really available from well-dated high-resolution archives. Extraordinarily rich archives of climate and palaeoceanographic change with seasonal resolution exist in deep inner shelf basins in the circum-Antarctic (e.g., Leventer et al., 2001, 2003; Domack et al., 2003).

The East Antarctic Margin (EAM) has received less attention in palaeoceanographic studies than West Antarctica, yet its role in deep ocean circulation and the global ocean–climate system is significant. For instance, a significant volume of shelf-derived Antarctic Bottom Water (definition by Orsi et al., 1999) originates along the Wilkes–Adélie coast (140–150°E) (Orsi et al., 1999; Rintoul and Bullister,

1999). In February–March 2001, cruise NBP01-01 of the RVIB *Nathaniel B. Palmer* cored the EAM from the George V and Terre Adélie coasts to the Edward VIII Gulf (inset Fig. 1) recovering thick deglacial to Holocene seasonally laminated (varved) diatom-rich sediments from several deep inner shelf basins (Domack et al., 2003; Leventer et al., 2001, 2003). Superficially, these sediments appear similar in lamination style and composition to those described from West Antarctica (e.g., Pike et al., 2001; Leventer et al., 2002; Maddison et al., in press) and, therefore, have the potential to provide seasonal-scale deglacial climatic information for the EAM. All NBP01-01 core sites recovering varved diatom-rich sediments (inset Fig. 1) share: (1) a similar geomorphological setting, that of a deep basin on the shelf, and (2) a similar lithostratigraphy, that of a glacial diamict overlain abruptly by the deglacial varved diatom-rich sediments (e.g., Leventer et al., 2003). The varved sediments grade into homogeneous, intermittently laminated, diatomaceous clays and muds of Holocene-age. The geochemistry and diatom content of the Holocene records have been previously described (Sedwick et al., 2001, 1998; Taylor and McMinn, 2001 and references therein) from short cores (~2–4 m length) collected during several earlier expeditions (Sedwick et al., 1998, 2001). The thickness of the deglacial varved sediments recovered during NBP01-01 is related to basin geometry and surrounding water depth. Diatoms are the main biogenic constituent of the varved sediments and are useful indicators of palaeoceanographic change, particularly in the Antarctic region where biogenic carbonate is relatively scarce, and opal flux is high. In typical open ocean settings of the Southern Ocean, rapid opal dissolution and grazing pressures mean that diatom thanatocoenosis on the sea-floor barely resembles the biocoenosis in the overlying surface waters. However, in localised regions where diatom productivity is exceptionally high and sedi-

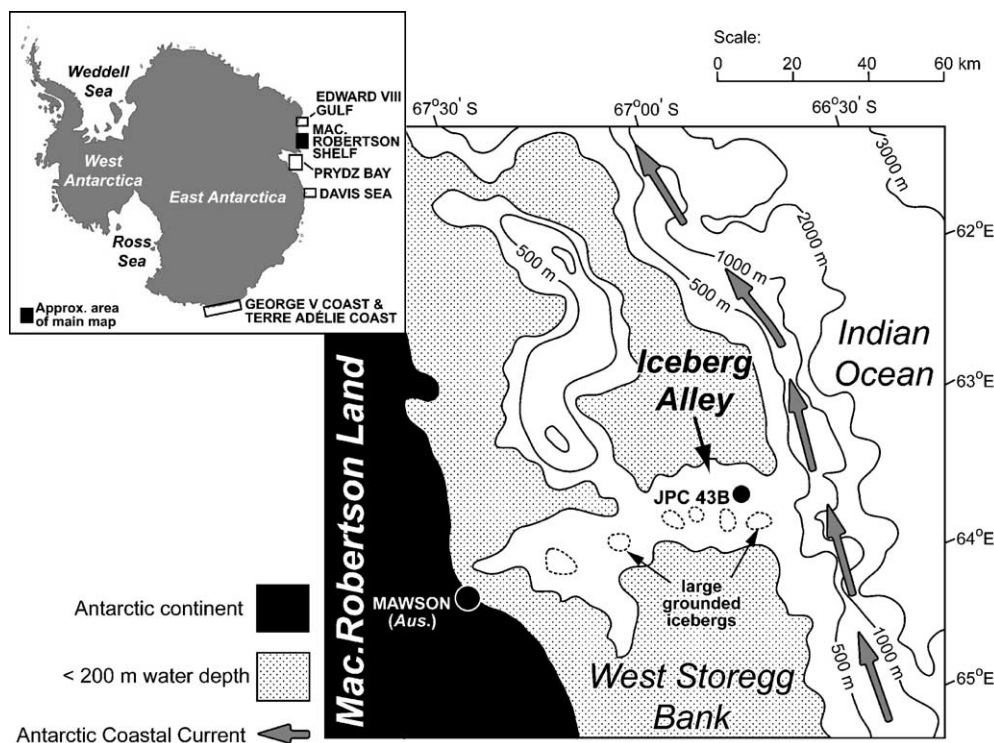


Fig. 1. Inset: General location of varved diatom-rich sediments recovered across the East Antarctic Margin during NBP01-01. Main: Bathymetric map of the Mac.Robertson Shelf in the vicinity of Iceberg Alley, indicating the location of Jumbo Piston Core 43B ($63^{\circ}07.376'E$, $66^{\circ}55.943'S$), and local oceanography. Bathymetric data from [GEBCO \(2000\)](#).

mentation rapid, such as those cored during cruise NBP01-01, frustule preservation potential far exceeds that of normal conditions. If carefully examined in a non-destructive manner, such sediments can reveal hundreds of years of palaeo-flux data. In this paper we present the first detailed microfabric study of the lower ~ 2 m of the deglacial varved sediments from core NBP01-01 JPC43B recovered from Iceberg Alley ($\sim 67^{\circ}S$, $63^{\circ}E$) on the Mac.Robertson Shelf (Fig. 1).

2. Iceberg Alley — geomorphological and oceanographic setting

Iceberg Alley, so-called because of grounded icebergs along both margins of its long-axis, is a long (~ 95 km), narrow (~ 25 km), SSW–NNE trending, deep basin (Fig. 1). The icebergs, grounded at 50–300 m water depth, reveal clues about the basin's recent glacial history and the genesis of

the varved sediments contained within it. Iceberg Alley is one of several, steep-sided, deep basins on the Mac.Robertson Shelf (MRS), gouged by glaciers and currents during the Quaternary (O'Brien et al., 1994; Harris and O'Brien, 1996). These basins act as sediment traps for siliceous mud and ooze (Domack, 1988; Harris and O'Brien, 1996, 1998).

Circumpolar Deep Water (CDW) is the most abundant water mass by volume influencing the MRS today (Smith et al., 1984). This relatively warm water mass is modified (Jacobs, 1989) as it mixes with Antarctic Surface Water (AASW — a summer shelf water mass defined by Whitworth et al., 1998). In East Antarctica modified Upper CDW upwells onto the outer MRS (e.g., Heil et al., 1996; Harris, 2000). Here it mixes and cools on the outer shelf banks via the Antarctic Coastal Current (ACoastC, Fig. 1) (Harris and O'Brien, 1998; Harris, 2000), a strong shelf current flowing westwards

along the EAM, capable of eroding gravel-sized material (Harris and O'Brien, 1996, 1998). Upwelled modified Upper CDW is prohibited from intruding further onto the shelf by the shallow (<200 m) outer shelf banks (e.g., West Storegg Bank, Fig. 1) (Harris, 2000), however, it likely

intrudes into the deeply incised basins such as Iceberg Alley during ice-free periods. This continental shelf access route for Upper CDW is suggested for the nearby Nielsen Shelf Valley (Harris, 2000) and for the Mertz glacial trough (George V Coast, Fig. 1) (Rintoul, 1998).

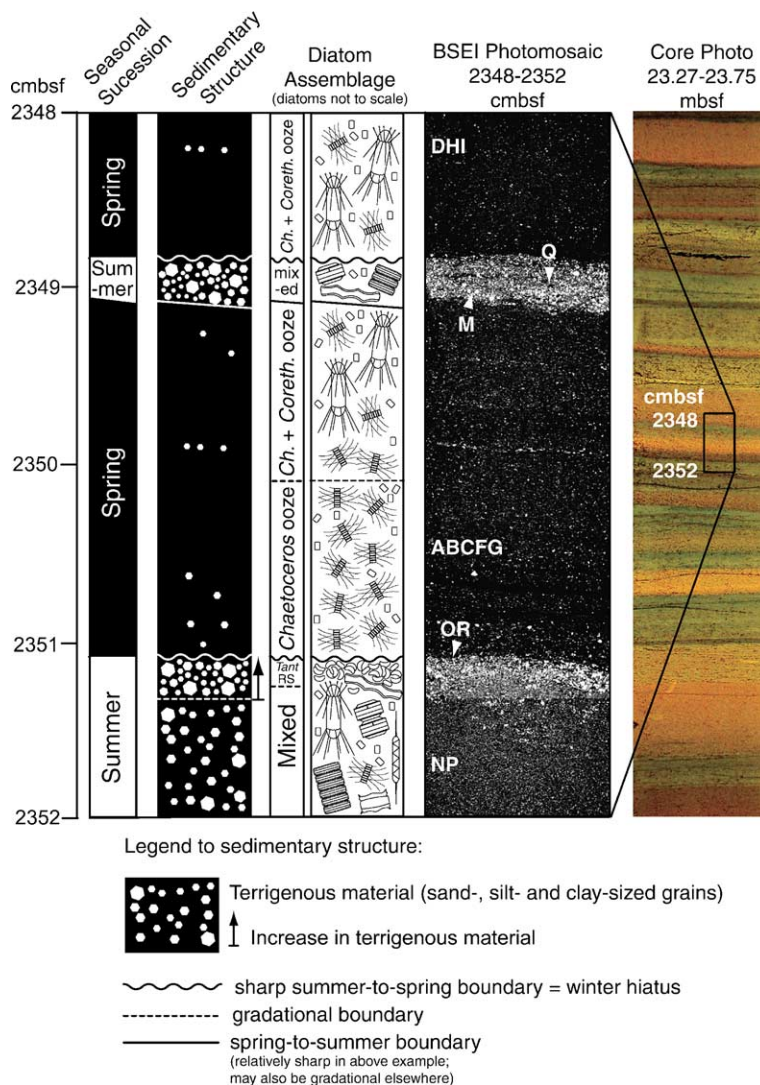


Fig. 2. Core photograph, backscattered electron imagery (BSEI) photomosaic, graphic log and interpreted seasonal signal for a selected section near the base of the deglacial varved sediments. The core photo (23.27–23.75 mbsf) indicates the striking colour variation between laminations. The BSEI photomosaic, for the section 2348–2352 cm below sea floor (cmbsf) is shown to the left of the core photo. Note how the brown/blue-grey terrigenous laminae appear bright in backscatter, while the orange/orange-brown diatom oozes appear dark. The boundary at the base of the diatom oozes is sharp, indicating the winter hiatus. The diatom assemblage (*Ch.* = *Chaetoceros*; *Coreth.* = *Corethron*; *TantRS* = *Thalassiosira antarctica* resting spores), sedimentary structure and seasonal interpretation of the sequence are indicated to the left of the BSEI photomosaic. Lettering on the photomosaic refers to some of the images presented in Figs. 4 and 5.

Several jumbo piston cores, up to 25 m in length, were recovered from Iceberg Alley during cruise NBP01-01. The recovered sediments appear undisturbed and are protected from ACoastC scour occurring further seaward over the outer MRS and upper shelf slope (Harris and O'Brien, 1996, 1998). Here we present results from one core, JPC43B, containing a relatively expanded (~1 kyr) deglacial varved sequence, with excellently preserved diatom assemblages and sedimentary micro-fabrics, throughout. These qualities make JPC43B an excellent archive of climate change on a number of timescales, and provide an exceptional opportunity to reconstruct diatom seasonality for deglacial times from the EAM. In this respect, JPC43B will become a reference section for future studies of this nature and locale.

3. Materials and methods

3.1. JPC43B core description

Core NBP01-01 JPC43B (63°07.376'E, 66°55.943'S; 23.96 m length) was recovered from the deepest part of the NNE, outer-shelf end of Iceberg Alley, at a water depth of 465 m (Fig. 1). Jumbo piston coring did not penetrate the glacial diamict. However, nearly 5 m of deglacial-age continuously laminated sediments were recovered from the base of the core at 23.96 m below sea floor (mbsf) to 19.13 mbsf. The core was photographed and visually described at the Antarctic Research Facility, Florida State University in January 2003. The varves comprise lamina couplets of (i) thick laminae/thin beds of orange/orange-brown very pure

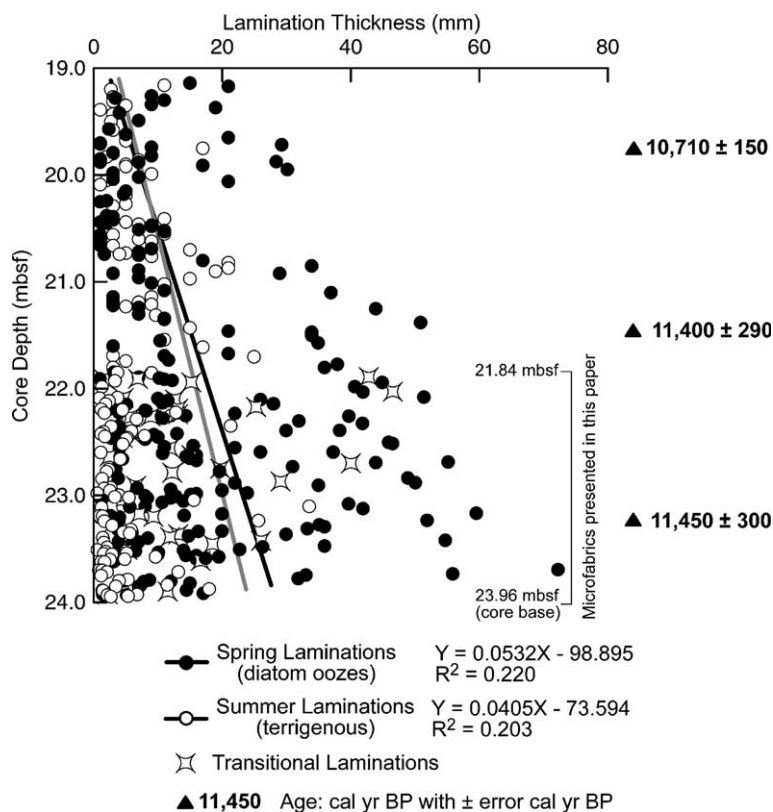


Fig. 3. Lamination thickness versus core depth for the deglacial varved sediments (19.13–23.96 mbsf) in JPC43B. Measurements below 21.84 mbsf are taken from BSEI photomosaics, with an error of ± 0.01 mm (thickness) and ± 0.01 mm (depth). Measurements above 21.84 mbsf are taken from core photographs for couplet pairs approximately every 5 cm core depth, with an error of ± 1 mm (thickness) and ± 5 mm (depth). Depths indicate lower lamina boundaries. Since transitional laminae are only recognised through BSEI analysis these are indicated below 21.84 mbsf only. Calibrated ages (Table 1) are indicated on the right.

diatom ooze, and (ii) brown/blue-grey diatom-rich terrigenous silt and clay. The colour core photograph in Fig. 2 illustrates the striking colour variation between laminae.

In general, lamina thickness decreases upcore for both the diatom oozes and the terrigenous laminae (Fig. 3). However below ~21.7 mbsf, both thick and thin laminae occur giving some scatter in the regression plot. Although the trend is not clear cut, the diatom oozes tend to be thicker than the terrigenous laminae particularly in the lower part of the sequence where the former can reach thicknesses of ~7.5 cm.

3.2. Core chronology

Chronology for JPC43B was based on 11 AMS radiocarbon dates (Table 1). Five dates were derived from rare carbonate shells ('carb', Table 1): articulated bivalves from 12.69 and 14.98 mbsf, a bivalve shell from 2.22 mbsf, a brittle star from 19.75 mbsf and a large foraminifera from 13.33 mbsf. The remaining six dates were derived from decalcified bulk organic matter ('decal. TOC', Table 1). All samples were analyzed at the Lawrence Livermore National Laboratory Center for Accelerator Mass Spectrometry

(CAMS) and ages were calibrated using CALIB 4.4.2 (© 1986–2004 M. Stuiver and P.J. Reimer) assuming a local reservoir age of 1700 ± 200 years (P. Sedwick, pers. comm., 2004). Note that most of the dated bulk organic matter is likely produced within the photic zone whereas the carbonates are benthic, and that the carbonate ages are slightly younger than the decalcified TOC dates. One explanation for this is that the radiocarbon content of bottom waters is higher than surface waters, which may result from surface waters being fed by upwelling Circumpolar Deep Water and local bottom waters being derived from coastal convection. Alternatively, the slightly older ages for the bulk organic matter may reflect a background addition of old carbon derived from shelf sediment erosion and transport. However, the relative consistency of the two types of dates adds strength to the overall chronology. One date from 17.25–17.30 mbsf is disregarded and a second order polynomial was fit to the curve to develop the chronology. Given these data, the varved unit at 19.13–23.96 mbsf can be dated to ~10,000 to ~11,000 cal yr BP (Fig. 3).

3.3. Laboratory procedures and analytical techniques

Varves were sampled using a sediment slab-cutter (Schimmelmann et al., 1990). The cutter was used to take overlapping sections of sediment, 15 cm in length, 1 cm thick and up to 3 cm wide, along the length of the core (e.g., Pike and Kemp, 1996; Dean et al., 1999). In this manner, varve integrity is preserved, and successive overlapping slabs are used to reconstruct the entire sequence. Analyses of slabs taken between 21.84 and 23.96 mbsf are presented in this paper. Slab cuttings were sliced into ~0.5 cm thick, 1.5 cm wide overlapping samples up to 4 cm in length, and embedded using the fluid-displacive low-viscosity Spurr resin embedding technique outlined by Pike and Kemp (1996) and adapted by Kemp et al. (1998). Highly polished thin sections were prepared for scanning electron microscope (SEM) backscattered electron imagery (BSEI) from the resin-embedded samples. BSEI analyses of the thin sections were carried out using an analytical LEO S360 SEM following the methods outlined by Kemp (1990) and Pike and Kemp (1996). Laminae and sublaminae were logged for composition and sediment fabrics at magnifications up to $\times 1500$, from

Table 1

Age-model data for Jumbo Piston Core 43B. mbsf = metres below sea floor; carb = carbonate shells (articulated bivalves, brittle star, large foraminifera); decal

Depth (mbsf)	Median depth (mbsf)	Type	^{14}C age (yr BP)	Calibrated age (cal yr BP)
2.22	2.22	carb	2755 ± 40	800 ± 200
5.05–5.10	5.075	decal. TOC	5539 ± 40	4330 ± 270
8.10–8.15	8.125	decal. TOC	7300 ± 40	6420 ± 220
12.69	12.69	carb	8375 ± 40	7560 ± 180
13.33	13.33	carb	9405 ± 40	8590 ± 215
14.07–14.12	14.095	decal. TOC	9852 ± 50	8980 ± 160
14.98	14.98	carb	9200 ± 40	8360 ± 225
17.25–17.30	17.275	decal. TOC	$13,500 \pm 45$	–
19.75	19.75	carb	$10,870 \pm 40$	$10,710 \pm 150$
21.38–21.43	21.405	decal. TOC	$11,663 \pm 40$	$11,400 \pm 290$
23.10–23.15	23.125	decal. TOC	$11,770 \pm 45$	$11,450 \pm 300$

TOC = decalcified bulk organic matter; ^{14}C age (yr BP) = reservoir corrected ages, using a local reservoir age of 1700 ± 200 years (P. Sedwick, pers. comm., 2004). Calibrated age (cal yr BP) = ages calibrated to calendar years. Calibrated ages for the deglacial varved sediments are indicated in Fig. 3.

BSEI photomosaics taken at $\times 20$ magnification. Logged information includes diatom floral assemblages, quantity and particle size of terrigenous material, thickness of (sub-)laminae and textural features (grading, sorting, degree of bioturbation and nature of (sub-)laminae boundaries). Analyses of smear-slides and secondary electron imagery (SEI) analysis of lamina-parallel fracture surfaces aided diatom species identifications. SEI analysis was carried out using a FEI XL30 FEG Environmental Scanning Electron Microscope.

Remarks on relative diatom abundance are based on cell density counts, defined by the number of diatom frustules within a $40,000 \mu\text{m}^2$ area of any given BSEI image according to the following categories: Dominant: >100 frustules; Abundant: 50–99 frustules; Common: 2–49 frustules; Rare: 1 or fewer frustules.

4. Results

4.1. General observations

One hundred and ninety-two laminae were investigated. The BSEI photomosaic (Fig. 2) covering an interval of 4 cm between 23.48 and 23.52 mbsf illustrates details of selected laminations and lamina boundaries. The orange/orange-brown laminae comprise almost pure, commonly near monogeneric, porous, diatom ooze (Fig. 4) and as such appear dark in the BSEI photomosaic (Fig. 2), whereas the brown/blue-grey laminae are less porous containing a mixed diatom flora and terrigenous material (Fig. 5), and therefore appear brighter (see Krinsley et al., 1983; and e.g., Dean et al., 1999 for explanation). Quantitative analysis of 5 couplet pairs indicates an absolute diatom abundance of between ~ 16.9 and $\sim 73.8 \times 10^8$ valves/g for the diatom oozes, and between ~ 2.5 and $\sim 8.2 \times 10^8$ valves/g for the terrigenous laminae. The upper boundaries of the terrigenous laminae are generally sharp (Figs. 2 and 5O), however, occasionally transitional laminations, exhibiting properties of both types of lamination, grade between the diatom oozes and the terrigenous laminae. Moreover, there is little bioturbation in the studied laminae although at high magnification (e.g., $>\times 20$) some biological disturbance is evident, which is most noticeable at lamina-

tion boundary intervals where material may be redistributed by 1 mm. However, disturbance is typically much less than this. Faecal pellets (e.g., Fig. 5O) are also common, particularly within the thicker diatom oozes, where their abundance tends to increase through individual laminae.

Analysis at magnification up to $\times 1500$ (Figs. 4 and 5) reveals details of the textural and floristic differences between the diatom oozes and the terrigenous laminae.

4.2. Diatom oozes

Eighty-two orange/orange-brown diatom ooze laminae were investigated. Laminations range in thickness from 0.53–75.03 mm (mean = 13.72 mm; $\sigma = 14.54$) and comprise nearly pure diatom ooze with minimal terrigenous material. Commonly three low diversity assemblages occur, defined by the dominant diatom genera or species. [NB: references to *Chaetoceros* spp. are species of the subgenus *Hyalochaetae* Gran, 1897, unless specified. Also, we follow the taxonomic notes by Armand and Zielinski (2001) for species of *Rhizosolenia*].

Assemblage (1) characterised as *Chaetoceros* spp. ooze (Fig. 4A–B, F), comprises a near monogeneric assemblage of *Chaetoceros* spp. vegetative cells and resting spores. Generally the ratio vegetative cells/resting spores decreases upward through the lamination. *Chaetoceros* spp. ooze is the most common assemblage of the studied interval (Table 2). The most pure *Chaetoceros* spp. oozes tend to be reddish in colour. *Corethron criophilum* (Fig. 4D), *Eucampia antarctica* vegetative cells, *Fragilariopsis cylindrus* (Fig. 4C) and/or *F. curta* (Fig. 4G) are occasionally present, but in rare abundance.

Assemblage (2) is characterised as *Chaetoceros* spp. + *Corethron criophilum* ooze (Fig. 4H–I). *Fragilariopsis curta* is typically present, while *Eucampia antarctica* vegetative cells, *F. cylindrus*, *Rhizosolenia antennata* f. *semispina* and *Proboscia inermis* are occasionally present in rare abundance. The sediment tends to be slightly ‘cottony’ in texture. In one lamination *Chaetoceros* spp. decreases in abundance near the top of the lamination leaving almost pure *C. criophilum* ooze (Fig. 4J).

Assemblage (3) characterised as *Chaetoceros* spp. + *Corethron criophilum* + *Rhizosolenia* spp. ooze

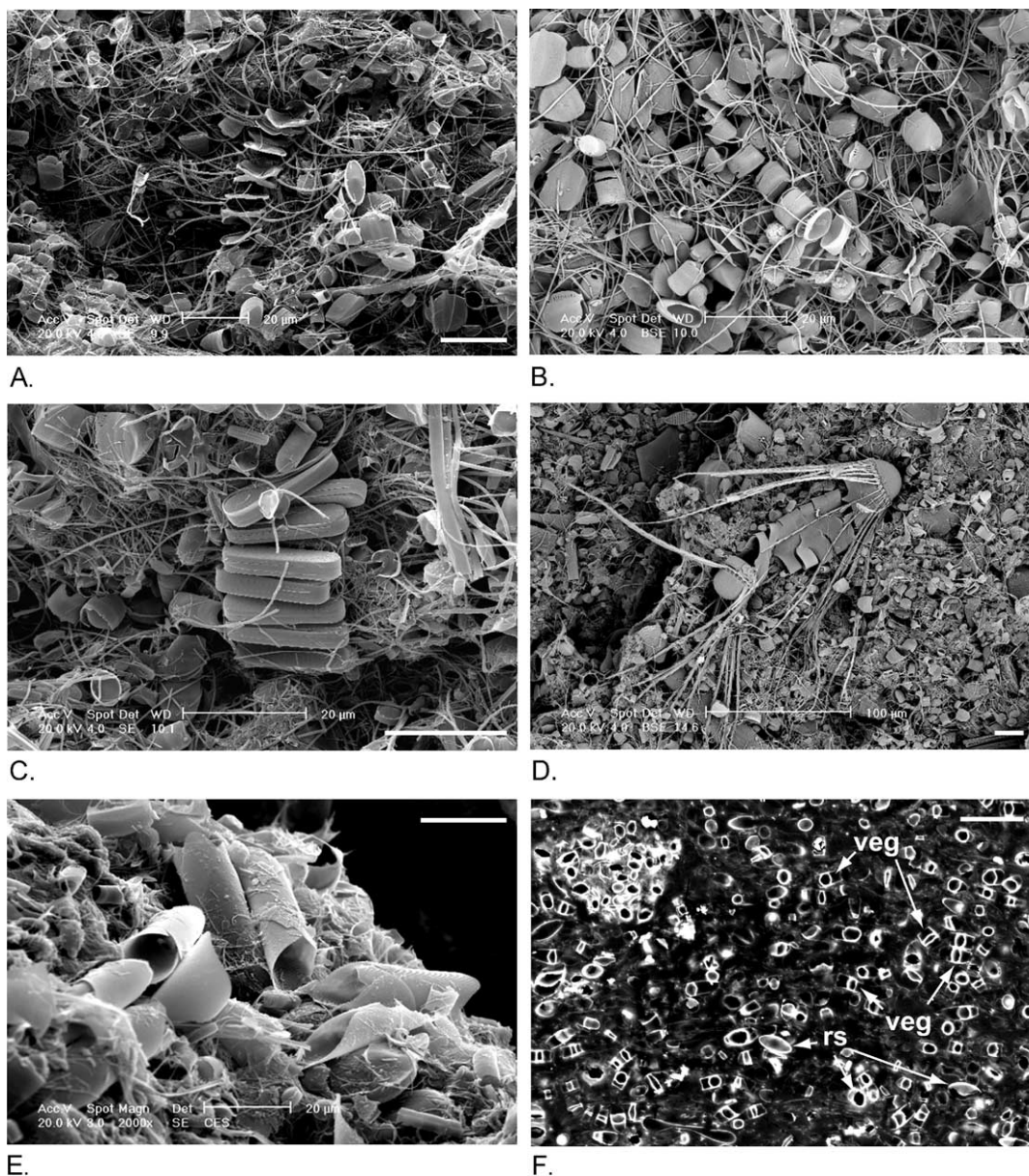


Fig. 4. High magnification images of typical spring laminations. A–E, lamina-parallel fracture surfaces (A, C and E secondary electron images; B and D backscattered electron images); F–L, backscattered electron imagery (BESI) of highly polished thin-sections. See Fig. 2 for position of images (note, images E, J, K and L are from higher up in the sequence). Scale bar = 20 µm. A and B. Vegetative *Chaetoceros* spp. colonies of the subgenus *Hyalochaete* Gran 1897 (A = *Ch. neglectus*; B = *Ch. neglectus* with resting spores) within an almost pure *Chaetoceros* spp. ooze. Vegetative chains and setae are abundant here and indicate the early spring bloom. C. *Fragilariopsis cylindrus* colony within *Chaetoceros* spp. ooze. D. *Corethron criophilum* frustule near the top of *Chaetoceros* spp. ooze. E. *Rhizosolenia* girdle bands near the top of *Chaetoceros* spp. + *Corethron criophilum* + *Rhizosolenia* spp. ooze. F. Almost pure *Chaetoceros* spp. ooze, comprising mainly vegetative cells (veg) and a few resting spores (rs). Note small faecal pellet in top left corner. G. *Fragilariopsis curta* colony within *Chaetoceros* spp. ooze. Colony is ~140 µm long. H and I. *Chaetoceros* spp. (Ch; everywhere in background) + *Corethron criophilum* (Ccri) ooze. J. *Corethron criophilum* ooze, with a few *Chaetoceros* spp. The 'streaky' and 'speckled' appearance in the background is caused by numerous spines and setae. K. *Chaetoceros* spp. (everywhere in background) + *Corethron criophilum* (Ccri) + *Rhizosolenia* spp. (Rhiz) ooze. Ph = *Chaetoceros* spp. frustule of the subgenus *Phaeoceros* Gran 1897. L. Layer of *Rhizosolenia* spp. (larger oval-circular shapes) within *Chaetoceros* spp. + *Corethron criophilum* + *Rhizosolenia* spp. ooze.

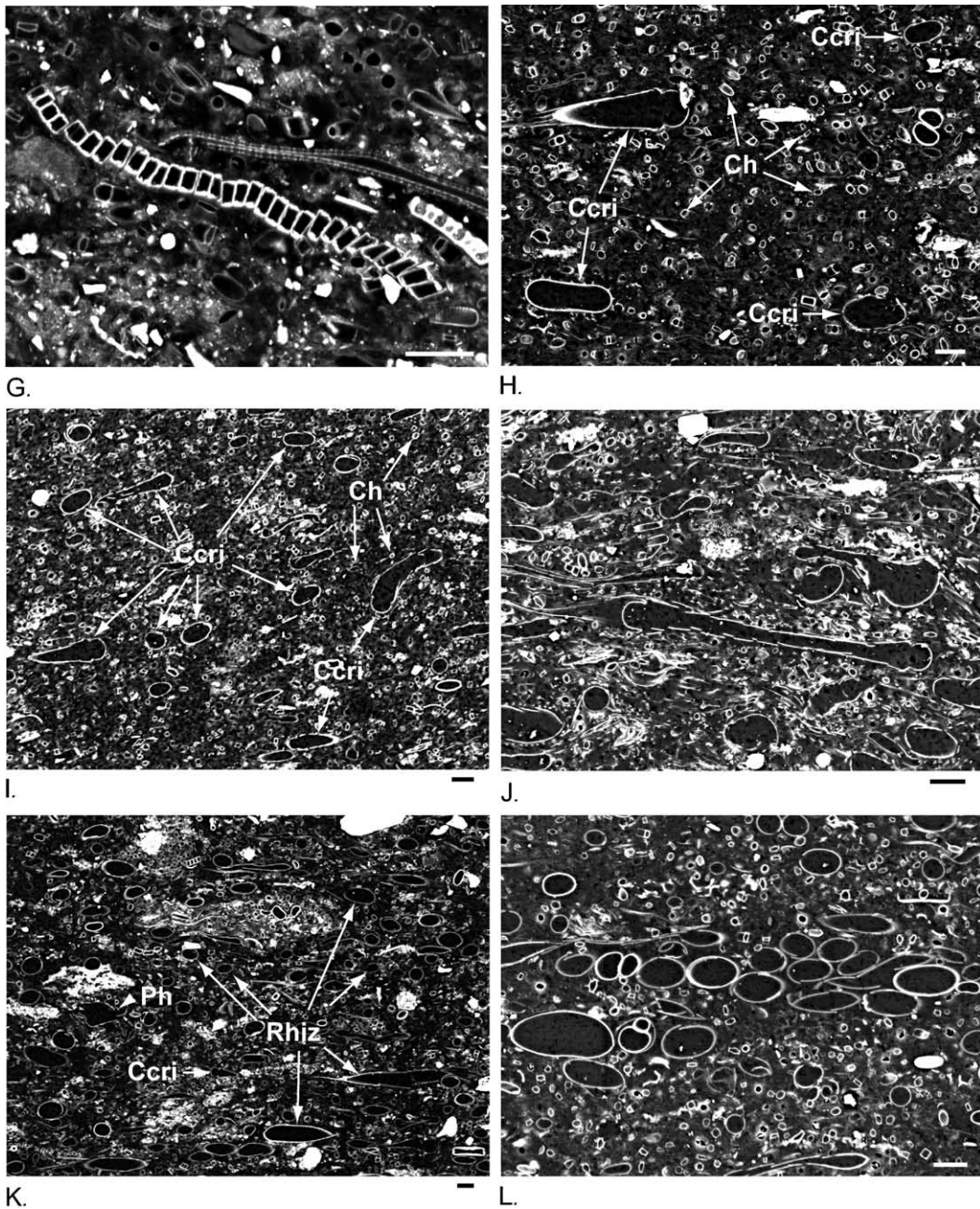


Fig. 4 (continued).

(Fig. 4E, K–L), occurs above ~23.41 mbsf (more frequently above ~23.07 mbsf) and includes typically *Rhizosolenia antennata* f. *semispina* but sometimes *Rhizosolenia antennata* f. *semispina* + *Proboscia iner-*

mis. Eucampia antarctica vegetative cells, *Fragilar-iopsis curta* and *F. cylindrus* are occasionally present in rare-common abundance; although *F. curta* is al-ways more abundant than *F. cylindrus*. *Chaetoceros*

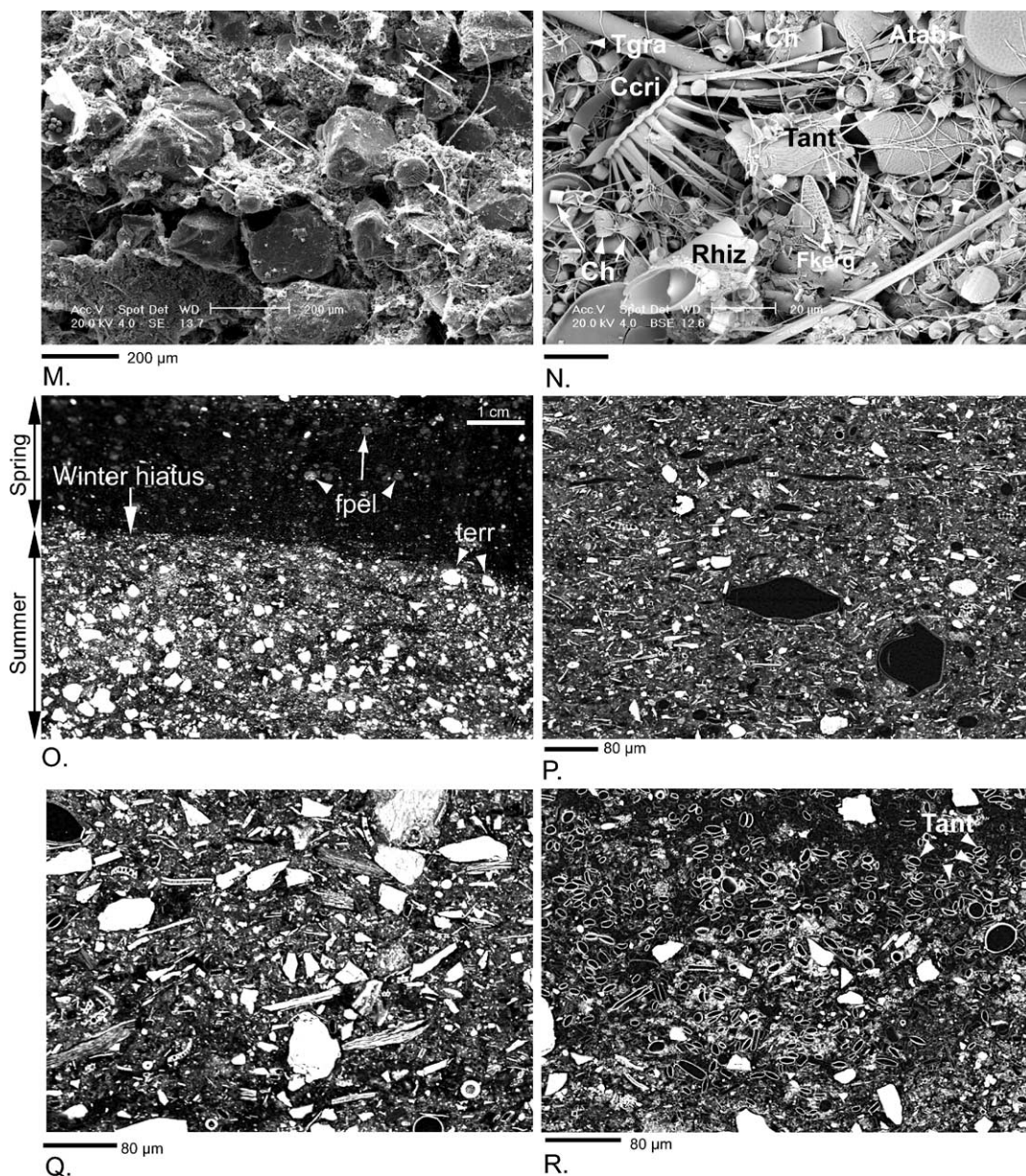


Fig. 5. High magnification images of typical summer laminations. M–N, lamina-parallel fracture surfaces in backscatter; O–R, backscattered electron imagery (BSEI) of highly polished thin-sections. See Fig. 2 for position of images. Scale bar = 20 μm, unless indicated. M. Angular silt- and sand-sized terrigenous grains with mixed diatoms. Larger diatoms indicated by arrows. N. Mixed diatom assemblage dominated by *Chaetoceros* spp. (Ch): *Azpeitia tabularis* (Atab); *Corethron criophilum* (Ccri); *Fragilariopsis kerguelensis* (Fker); *Rhizosolenia* spp. (Rhiz); *Thalassiosira antarctica* (Tant); *Thalassiosira gravida* (Tgra). O. Typical boundary between summer (below) and spring (above) laminations. The boundary is sharp, representing the winter hiatus in deposition due to seasonal sea-ice cover. The white patches and grey areas within the summer lamination are silt- and clay-sized terrigenous grains (terr). The grey rounded patches within the spring lamination are faecal pellets (fpel), rich in clay-sized material and diatoms. The dark patches in both laminations are diatom-rich regions. P and Q. Terrigenous material (bright areas and patches) and mixed diatoms (dark areas; note the variety of sizes and shapes). The 2 largest diatoms in image P are *Coscinodiscus bouvet* frustules. Note the difference in type of terrigenous material between the 2 images; there is an abundance of mica in image Q (platey grains), while they are less abundant in image P. R. Sublamination of *Thalassiosira antarctica* resting spores (kidney-bean shapes; Tant) near the top of a summer lamination.

Table 2

Diatom assemblage and intra-lamina assemblage sequence for the orange/orange-brown diatom oozes within the studied interval, 21.84–23.96 mbsf

Assemblage	Frequency	Depth range (mbsf)	Thickness range (mm)
Assemblage (1)	63 total. [7]	21.84–23.96 [22.55–23.84]	0.88–72.48
Assemblage (2)	16 total. [5]	21.91–23.95 [23.82–22.46]	0.53–34.90
Assemblage (3)	11 total. [4]	21.98–23.41 [22.46–23.06]	2.97–48.93
Assemblage sequence			
Assemblage (1) followed by Assemblage (2)	4	23.33–23.82	10.23–75.03
Assemblage (1) followed by Assemblage (3)	3	22.54–23.07	19.35–52.42
Assemblage (2) followed by Assemblage (3)	1	Top 2245.52 cmbsf; Base 2245.81 cmbsf	5.94 mm thick

Their frequency (number out of 82 laminations investigated), depth and thickness ranges are indicated. Assemblage (1) = *Chaetoceros* spp. ooze; Assemblage (2) = *Chaetoceros* spp. + *Corethron criophilum* ooze; Assemblage (3) = *Chaetoceros* spp. + *Corethron criophilum* + *Rhizosolenia* spp. ooze. See text for fuller description of Assemblages (1) to (3). [Numbers in square parenthesis indicate the frequency that Assemblage (1), (2) or (3) occur as part of a sequence].

spp. of the subgenus *Phaeoceros* Gran, 1897 may be present in common abundance on occasion (Fig. 4K). The sediment tends to be slightly ‘cottony’ in texture. In two laminae *Chaetoceros* spp. and *C. criophilum* disappear near the top of the lamination leaving pure *Rhizosolenia* spp. ooze. Ninety percent (74 laminations) of the diatom oozes investigated comprises one of either Assemblages (1), (2) or (3) (Table 2). However, ten percent (8 laminations) comprise a two- or three-stage intra-lamina sequence in strict numerical order. For example if occurring as part of an intra-lamina sequence, Assemblage (1) always occurs prior to (below in sediment) Assemblage (2) and/or Assemblage (3) (Table 2). Intra-lamina variation normally occurs within, but not in all of, the thicker laminations (those >~6 mm thick, Table 2), and is typically accompanied by a slight increase in clay at each stage. Table 2 gives the frequency of occurrence for individual assemblages and for the intra-lamina sequences. The overwhelming dominance of *Chaetoceros* spp. throughout the studied interval is apparent from these data.

Other diatoms are rare in the diatom oozes, however, where they do occur they tend to be large such as *Coscinodiscus bouvet*, *Odontella weissflogii* and *Stellarima microtrias*. In addition, *Thalassiosira antarctica* resting spores are also sometimes present in the diatom oozes, but always only as faecal pellets. These four species are more common in the terrigenous laminae however.

4.3. Terrigenous laminae

Seventy-one brown/blue-grey diatom-rich terrigenous laminations were investigated. Laminations range in thickness from 0.30–33.49 mm (mean=4.56 mm; σ =5.8) and comprise diverse, mixed ‘Antarctic’ diatom assemblages (Fig. 5N, P–Q) with sand-, silt- and clay-sized terrigenous material (Fig. 5M, O–Q). Terrigenous grains are angular, sub-angular, sub-rounded or platy (mica). Diatom assemblages typically include those taxa listed in Table 3 in varying abundance with occasional sponge spicules and planktonic and agglutinated foraminifera. Silicoflagellates (mainly *Distephanus speculum*) are also present, sometimes in high abundance. Some of the larger diatoms (e.g., *C. bouvet*) contain pyrite inclusions.

Although *Thalassiosira antarctica* resting spores are generally common to abundant throughout these laminations higher concentrations occur frequently (25 times) at the top of the terrigenous laminae just below the sharp boundary (Fig. 5O). Such concentrations are apparent in the BSEI images as thin to thick sublaminae (0.26–10.47 mm thickness range) or pseudo-sublaminae (i.e., horizontal integrity lost but nonetheless recognisable as a sublamination) (Fig. 5R). The *T. antarctica* sublaminae are occasionally mildly to moderately bioturbated into the diatom ooze above (Fig. 5R). The thickest *T. antarctica* sub-laminae tend to be accompanied by a

Table 3

Diatoms typically occurring in the brown/blue-grey diatom-rich terrigenous laminae

<i>Actinocyclus actinochilus</i>	<i>Fragilariopsis curta</i>	<i>Pseudo-nitzschia</i> spp.
<i>A. curvatulus</i>	<i>F. cylindrus</i>	
<i>Actinocyclus</i> spp.	<i>F. kerguelensis</i>	<i>Rhizosolenia antennata</i> f. <i>antennata</i>
	<i>F. obliquecostata</i>	<i>Rhizosolenia antennata</i> f. <i>semispina</i>
<i>Amphiprora</i> spp.	<i>F. pseudonana</i>	<i>Rhizosolenia</i> spp.
	<i>F. rhombica</i>	
<i>Asteromphalus hookeri</i>	<i>F. ritscheri</i>	<i>Stellarima microtrias</i>
<i>A. hyalinus</i>	<i>F. separanda</i>	
<i>A. parvulus</i>	<i>F. sublinearis</i>	<i>Stephanopyxis</i> spp.
	<i>Fragilariopsis</i> spp.	
<i>Azpeitia tabularis</i>		<i>Thalassiosira ambigua</i>
	<i>Manginea</i> spp.	<i>T. antarctica</i> Δ
<i>Chaetoceros</i> spp.*		<i>T. dichotomica</i>
	<i>Navicula</i> spp.	<i>T. gracilis</i> var. <i>expecta</i>
<i>Cocconeis</i> spp.		<i>T. gracilis</i> var. <i>gracilis</i>
	<i>Nitzschia</i> spp.	<i>T. grvida</i>
<i>Corethron criophilum</i>		<i>T. lentiginosa</i>
	<i>Odontella weissflogii</i>	<i>T. oestrupii</i>
<i>Coscinodiscus asteromphalus</i>		<i>T. oliverana</i>
<i>C. bouvet</i>	<i>Paralia</i> spp.	<i>T. poroseriata</i>
<i>C. ?centralis</i>		<i>T. ritscheri</i>
<i>C. radiatus</i>	<i>Plagiotropis</i> spp.	<i>T. trifulta</i>
<i>Coscinodiscus</i> spp.		<i>T. tumida</i>
	<i>Porosira glacialis</i>	<i>Thalassiosira</i> spp.
<i>Dactyliosolen antarctica</i>	<i>P. pseudodenticulata</i>	
		<i>Thalassiothrix antarctica</i>
<i>Eucampia antarctica</i> ‡	<i>Proboscia inermis</i>	
	<i>P. truncata</i>	<i>Trichotoxon reinboldii</i>

**Chaetoceros* spp. of the subgenus *Hyalochaetae* Gran, 1897 are dominant, although species of the subgenus *Phaeoceros* Gran, 1897 occur in rare abundance; ‡*Eucampia antarctica* vegetative cells and resting spores; Δ*Thalassiosira antarctica* vegetative cells and resting spores of the cold form described by Villareal and Fryxell (1983).

high concentration of clay-sized terrigenous grains, with or without silt, and by common to abundant occurrences of *Porosira glacialis*.

There is a notable variation in terrigenous grain-size, abundance and sorting within, and often between, laminations. For example, repetitive micro-grading is apparent through some of the laminations, whilst others exhibit poor, or even reverse grading. The largest grains (up to ~1.5 cm diameter) are found in the very oldest laminations near the base of the core. Where there is an abundance of mica (Fig. 5Q), there is also a high concentration of both organic material and neritic diatoms such as *Paralia* spp. and *Stephanopyxis* spp., and a notable lack of more offshore diatoms. This suggests occasional downslope displacement and re-sedimentation of shallower water material either from the coastal zone or the shelf banks.

4.4. Transitional laminations

We define transitional laminations as discrete layers bearing characteristics of both the diatom oozes and the terrigenous laminations. They are common (total 39) ranging in thickness from 1.26 to 46.57 mm (mean = 12.34; σ = 11.2) and occupy a core depth range of ~21.89–23.94 mbsf. Transitional laminae always grade upwards from a diatom ooze below and typically grade upwards into a terrigenous lamination above. Rarely, a transitional lamination may be superseded abruptly by the successive diatom ooze in the sequence (i.e., the terrigenous lamination is ‘missing’). Gradation occurs in terms of lamination colour, diatom content and quantity of terrigenous material. For example, an orange/orange-brown *Chaetoceros* spp. ooze may grade upward into an orange-

brown/brown (transitional) lamination containing mixed diatoms dominated by *Chaetoceros* spp. with moderate quantities of clay-and/or small silt-sized grains. This in turn may grade up into a typical brown/blue-grey diatom-rich terrigenous lamination, containing a mixed diatom flora and with a notable increase in clay-, silt- and sometimes sand-sized grains. Consistently, the floral content of the diatom ooze dictates which diatom(s) dominate in the superceding transitional lamination (e.g., a transitional lamination dominated by *Chaetoceros* spp. and *Corethron criophilum*, supercedes a diatom-ooze comprising the same). More rarely (9 times), sub-laminae of *T. antarctica* resting spores occur immediately above transitional laminae.

5. Seasonality recorded in the laminated diatom sediments

We assume that the laminae and sub-laminae described in this paper reflect discrete diatom productivity events. The challenge is to place these events within a time-frame, in order to understand local and regional oceanographic change and the temporal patterns of such change. Cyclicity on two frequencies is suggested: (i) sub-mm- to mm-scale represented by sub-laminae; (ii) mm- to cm-scale represented by couplet pairs. We discuss and suggest mechanisms for these variations.

5.1. Spring

We propose that the diatom oozes represent the deglacial spring bloom in Iceberg Alley, characterised by sea-ice melt, stratification, exceptionally high primary production and rapid opal flux to the seafloor.

Chaetoceros spp. blooms and their ensuing resting spores are widely known to indicate highly eutrophic conditions, in modern (Stockwell, 1991; Guillard and Kilham, 1977) and past environments (e.g., Donegan and Schrader, 1972; Schuette and Schrader, 1979). In Antarctica, their preference for near-shore or coastal environments is illustrated by core-top abundance data in the S. Atlantic (Zielinski and Gersonde, 1997) and Prydz Bay (Stockwell, 1991), while e.g., Hargraves and French (1983) show the relationship

between sea-ice and *Chaetoceros* spp. abundance. Moreover, Leventer (1991) and Crosta et al. (1997) demonstrate the relationship between high abundances of *Chaetoceros* spp. resting spores and highly stable, stratified waters associated with both glacial runoff and sea-ice melt. Leventer (1991, 1992) suggest that reduced salinity or nitrogen depletion near the sea-ice edge may trigger the formation of resting spores. *Chaetoceros* spp. resting spores are also known to overwinter in sea-ice (e.g., Ligowski et al., 1992) and to subsequently “seed” the spring population in the melt-zone when favourable growth conditions return during the spring melt. Based on this information, we suggest that the blooms of *Chaetoceros* spp. recorded in the diatom oozes within JPC43B indicate stratified, lower salinity and highly nutrient-rich surface waters associated with melting sea-ice in spring. Nutrients trapped in the meltwater lid at the surface sustain *Chaetoceros* production, followed by resting spore formation as nutrients are depleted. Throughout the season, *Chaetoceros* spp. vegetative cells and resting spores are likely to have undergone rapid sedimentation, possibly via self-sedimentation (Alldredge and Gotschalk, 1989; Grimm et al., 1997; Alldredge et al., 2002). We suggest continual sedimentation of *Chaetoceros* spp. throughout spring since multiple sedimentation episodes are not obvious within the laminations.

Besides *Chaetoceros*, the diatom oozes commonly contain *Corethron criophilum*. Where both diatoms occur within a spring lamination *C. criophilum* apparently always blooms at the same time, or after the initial *Chaetoceros* spp. bloom. Thus, in years when *Chaetoceros* spp. is not the sole dominant diatom blooming in spring, a typical spring succession is either: (i) *Chaetoceros* spp. followed by *Chaetoceros* spp. + *C. criophilum* or, (ii) co-occurring *Chaetoceros* spp. + *C. criophilum* without further succession (Table 2). Leventer et al. (1993) also report *Chaetoceros* spp. and *Corethron criophilum* bloom events in late Holocene sediments from Granite Harbor (McMurdo Sound, western Antarctica), and attribute this to strong surface water stratification. *Corethron criophilum* is cosmopolitan and widespread (e.g., Fryxell and Hasle, 1971; Fenner et al., 1976; Leventer et al., 1993 and references therein) with a preference for open water (i.e., ice-free) conditions. For example, Crawford et al. (1997) report a predominance of *C. crio-*

philum in the polar frontal region of the South Atlantic during the austral spring of 1992. In Iceberg Alley, an influx of *C. criophilum* occurring after the initial *Chaetoceros* bloom suggests an influx of warmer open water (under stratified conditions) following, or during the final stages of spring sea-ice melt. Diatom oozes lacking a pure *Chaetoceros* spp. sublamination at the base (i.e., those which record the co-occurrence of *Chaetoceros* and *Corethron* from their base upwards), suggest years where, either (i) sea-ice was perhaps not as concentrated as in other years—thus melting could occur more quickly allowing both diatoms to bloom together, or (ii) sea-ice density remained approximately constant each year, but the influx of a warmer water mass (allowing *Corethron* to move into Iceberg Alley) speeded up sea-ice melting. Conversely, laminations recording pure *Chaetoceros* ooze throughout (i.e., those completely lacking a *Corethron* stage) suggest years of, either (i) denser sea-ice, or (ii) no spring influx of warmer water. Either scenario would lead to a longer melting period, sustained and massive *Chaetoceros* production, and consequential high flux to the seafloor.

At ~23.41 mbsf and above, *Rhizosolenia*, dominated by *R. antennata* f. *semispina*, enters the diatom spring succession (Table 2, Fig. 6). Occasionally, the closely related genus *Proboscia* (almost entirely one species, *P. inermis*) co-occurs in secondary importance to *R. antennata* f. *semispina*. Where they occur, *Rhizosolenia* and *Proboscia* apparently always bloom at the same time or after the initial *Corethron criophilum* bloom. According to Armand and Zielinski (2001), *Rhizosolenia antennata* f. *semispina* is one of the most common and adaptable rhizosolenioids in the Southern Ocean. It has a wide temperature tolerance of -1 to $+12$ °C (Zielinski and Gersonde, 1997), and is found anywhere between the open ocean to within sea-ice. For example, distribution maps of its occurrence in surface sediments of the Atlantic Sector (Armand and Zielinski, 2001) show relatively high abundances between the modern mean winter sea-ice edge and the Polar Front, with the highest abundance at approximately the position of the mean winter sea-ice edge. In contrast, besides its taxonomy (Jordan et al., 1991) very little is reported on the distribution or ecological preferences of *Proboscia inermis*. Peters and Thomas (1996) report on

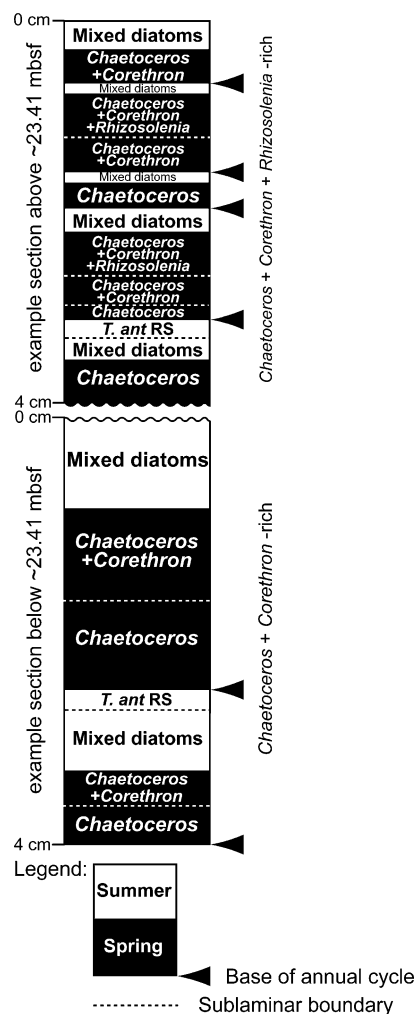


Fig. 6. Typical annual diatom sequences for two 4 cm core sections above and below ~23.41 mbsf. We use the base of spring laminae as an annual chronometer.

its capability to survive prolonged periods of darkness in the Antarctic but its association with *R. antennata* var. *semispina* in JPC43B suggests a similar open ocean provenance. We suggest that these two rhizosolenioids, occurring sometime after the initial *Chaetoceros* and *Corethron* spring blooms indicate an increasing influence of oligotrophic, offshore, warmer waters to Iceberg Alley in late spring, as the deglaciation progressed. These changes in diatom content are simple observations, yet they have far reaching implications for the local to regional palaeoceanography of the EAM. For instance, the presence and absence

patterns of *Corethron* and *Rhizosolenia* through JPC43B may point towards cyclicity in the influx of the water mass, nutrient source, and/or environment, responsible for causing and/or sustaining blooms of these diatoms in Iceberg Alley.

Fragilariopsis curta and *F. cylindrus* are rare to common in some of the diatom oozes but exhibit no typical successional pattern. Sometimes, they occur rarely throughout an entire lamination; in other laminations, concentrations or pseudo-sublaminae of these taxa occur either within the lower, or the upper part, of the lamination. *F. curta* is endemic to the Southern Ocean, while *F. cylindrus* has a bipolar distribution (Hasle, 1976). In the circum-Antarctic, both species have a wide distribution from offshore to nearshore environments (Zielinski and Gersonde, 1997). However, their highest abundances occur in coastal regions influenced by sea-ice (Truesdale and Kellogg, 1979; Leventer and Dunbar, 1988; Leventer, 1992, 1998; Zielinski and Gersonde, 1997; McMinn et al., 2001), south of the winter sea-ice edge (Atlantic Sector; Zielinski and Gersonde, 1997). Both taxa have also been reported living within sea-ice (e.g., Palmisano and Garrison, 1993; Clarke et al., 1984; Armand, 2000) and beneath sea ice (e.g., Burckle et al., 1987; Fryxell et al., 1987). Like *Chaetoceros* during spring sea-ice melt, *F. curta* and *F. cylindrus* can 'seed' the surrounding nutrient-rich, stratified waters and bloom (e.g., Fryxell, 1989; Kang and Fryxell, 1992; Cunningham and Leventer, 1998). Their presence corroborates our suggestion of sea-ice related spring deposition for the diatom oozes in JPC43B.

5.2. Summer

We propose that the terrigenous laminae represent the deglacial summer season in Iceberg Alley, characterised by an influx of 'offshore' waters, water column mixing, reduced primary production, open water diatoms and an increased influx of terrigenous material (or reduced dilution by biogenics) to the seafloor.

Composition of the diatom assemblages in the terrigenous laminae is typical of those described from surface sediments south of the Polar Front within the circum-Antarctic biogenic opal belt (e.g., Zielinski and Gersonde, 1997; Crosta et al., 1998a,b), and

indicates open water production in well-mixed waters (e.g., Leventer, 1998). For example, *Fragilariopsis kerguelensis*, *Porosira glacialis*, *Thalassiosira antarctica* resting spores, *T. lentiginosa* and *T. gracilis* var. *expecta* typically occur in common to high abundance in the terrigenous laminae. *F. kerguelensis* and *T. lentiginosa* are reported to occur in all regions of the Southern Ocean from the Subtropical Front to the position of the mean winter sea-ice edge (e.g., in the Atlantic Sector of the Southern Ocean according to Zielinski and Gersonde (1997)). In the case of *F. kerguelensis* higher abundances are observed distal from the coast in the Atlantic Sector (Zielinski and Gersonde, 1997), the Ross Sea (Truesdale and Kellogg, 1979) and the George V Coast (Leventer, 1992). *T. gracilis* var. *expecta* is also known from the open ocean (e.g., Taylor et al., 1997), while *T. antarctica* and *P. glacialis* have a preference for near-shore, shelfal environments (e.g., Taylor et al., 1997; Zielinski and Gersonde, 1997). In effect, the diatom assemblages preserved in the terrigenous laminae resemble the 'shelf' and 'oceanic' assemblages defined statistically by Taylor et al. (1997) for surface sediments in nearby Prydz Bay. Warmer water, temperate taxa with maximum occurrences to the northern edge of the opal belt, i.e., north of the Polar Front (e.g., Zielinski and Gersonde, 1997), do not occur or are exceptionally rare in JPC43B.

Thalassiosira antarctica resting spores typically occur throughout the summer laminae, however, the presence of a single, discrete sub-lamination of this species at the top of approximately a third of the summer laminae is an important observation, and provides information about the seasonality of this enigmatic diatom. *T. antarctica* resting spore sublaminae often also contain a significant abundance of *Porosira glacialis*, which suggests similarity in their growth requirements. Relatively little is known about the ecological preferences of *T. antarctica*, but from a few sediment trap studies and analysis of core-top material, it appears to thrive in Antarctic near-shore environments (e.g., Hasle and Heimdal, 1968; Zielinski and Gersonde, 1997; Cunningham and Leventer, 1998), and is associated with sea-ice, low temperatures and low salinities (e.g., Hasle and Heimdal, 1968; Villareal and Fryxell, 1983). For example, it has been observed growing in frazil and platelet ice formed under turbulent conditions (Weddell Sea;

Gleitz et al., 1998). Bartsch (1989) and Aletsee and Jahnke (1992) show from culture experiments that *T. antarctica* can grow in reduced light conditions even at temperatures as low as -4°C . Furthermore, the vegetative cells can survive within sea-ice (Aletsee and Jahnke, 1992) for prolonged periods of darkness without forming resting spores (Peters and Thomas, 1996). Instead, diatom resting spore formation is likely triggered by nutrient stress (e.g., Hargraves and French, 1975, 1983; Syvertsen, 1979) and in the case of *T. antarctica* up to four resting spores can be formed from a single cell (Fryxell et al., 1981; Doucette and Fryxell, 1985). A single, relatively thin, sub-lamination of *T. antarctica* resting spores in JPC43B, implies a single, relatively short, episode of resting spore formation and flux at the end of some summers or even early autumn when seasonal nutrients have been depleted and new sea-ice is forming. This corroborates the findings of Cunningham and Leventer (1998) who suggested an autumnal bloom event for this diatom based on surface sediment samples from the Ross Sea. However, in JPC43B most summer laminae lack an uppermost sub-lamination of *T. antarctica* resting spores, which indicates that either conditions were unfavourable for a late summer/autumn bloom of this species and/or formation of its resting spores, or its resting spores were not preserved in the sediment.

The influx of terrigenous material to the basin floor during the deglacial summer is a seasonal melt-water overprint signal on the large-scale permanent ice-sheet retreat during the deglaciation. Ice-rafted detritus in surficial sediments is present in all regions of the MRS, but is more common in mid- to outer-shelf sediments from deep-water shelf basins (Harris and O'Brien, 1996) (i.e., outer-shelf end of Iceberg Alley in the region of JPC43B, Fig. 1). Harris and O'Brien (1998) note a higher concentration of ice-rafted detritus in the lower sections of post-glacial laminated sediment in nearby Nielsen Basin on the MRS (inferences from their Fig. 14). They interpret this as rapid glacial melting and trapped icebergs against the edge of the calving front over their core sites. A similar scenario is possible for Iceberg Alley. Periodic redeposition of shallow-water ($<200\text{ m}$) material from the margins to the central, deeper parts of Iceberg Alley is suggested for those laminae containing a strong association of mica grains and neritic (e.g., tychopelagic)

diatoms. Down-washing of these shallow-water, shelfal sediments may have been caused by shifting icebergs or local currents.

5.3. Annual cyclicity

We have suggested, on textural and biogenic evidence that the diatom oozes represent the deglacial spring season, while the terrigenous laminae represent deglacial summer in Iceberg Alley; a reflection of the modern seasonal flux variation for sea-ice influenced regions of the circum-Antarctic. Hence, couplet pairs represent annual deposition where the autumn season may be partly present, and winter is represented by a single hiatus immediately below the successive spring lamination (Fig. 2). A summary of the typical annual diatom sequences for two 4 cm core sections above and below $\sim 23.41\text{ mbsf}$ is depicted in Fig. 6. We use the onset of the spring laminae as our basic annual chronometer since this event is recurrent and very distinctive in the BSEI photomosaics (Fig. 2). Our data show that deglacial spring and summer are partly or wholly ice-free in Iceberg Alley, while sea-ice may begin to form in late summer or autumn. The succession of diatoms from ice-seeded, to ice-edge to open ocean taxa has also been noted from sediment trap studies (e.g., Armand, 2000 and references therein) and reflects the decreasing sea-ice influence through the annual cycle. Therefore, we can be confident that couplet pairs within JPC43B represent a single year, and not multiple years. Transitional laminae may represent years when the seasonal boundaries, defined by our floristic and textural data, is not as clear-cut as in other years.

5.4. Nutrient sources and mechanisms for high opal flux

We have demonstrated how deglacial marine varves in JPC43B record exceptionally high diatom flux to the sea floor following the retreat of permanent sea ice at $\sim 11,000\text{ cal yr BP}$. Moreover, high silica flux during the deglaciation appears to be a circum-Antarctic feature (Domack et al., 2003; Leventer et al., 2001, 2003). Abelman and Gersonde (1991) estimated that 70–95% of the annual modern flux of diatoms, in seasonally ice-covered regions of the Southern Ocean, occurs in the austral summer via

pulses of faecal pellets. We question this level of flux for deglacial conditions within Iceberg Alley. In JPC43B the majority of faecal pellets, by far, occur later in the spring season, following the initial spring bloom. Moreover, on lamination thickness alone, diatoms blooming in the spring season (maximum ~7.5 cm thickness; Fig. 3) contribute significantly more to the annual flux than those in the summer bloom (maximum ~3.3 cm thickness; Fig. 3). These thick diatom ooze laminations/thin beds reflect exceptionally high seasonal diatom production (blooms), as well as some sediment focusing, signifying a huge annual export flux of biogenic silica, and carbon, during the early deglaciation.

The nutrient source and supply mechanism to trigger and sustain such exceptionally high spring productivity is of interest. Two sources are possible; (i) dust release from the seasonal sea-ice melt enhanced considerably by that from the retreating ice-sheet, and (ii) incursions of modified Upper Circumpolar Deep Water (CDW) on the outer MRS. Both sources are considered in brief here. Fundamentally, diatoms require reactive CO₂, nitrate, phosphate and silicic acid for reproduction and frustule formation. Moreover iron, a well-known bio-limiting nutrient (e.g., Coale et al., 1996; Martin and Fitzwater, 1988; De Baar et al., 1995; Boyle, 1998; Hutchins and Bruland, 1998; Takeda, 1998; Boyd et al., 2000) stimulates diatom production (e.g., De Baar et al., 1995; Takeda, 1998) and controls the degree of silicification (e.g., Hutchins and Bruland, 1998). A rich supply of iron, for example, reduces the silicic acid:nitrate uptake ratio in diatoms, resulting in thinner frustules (Boyle, 1998). When iron is deficient, not only are diatoms more heavily silicified (e.g., Hutchins and Bruland, 1998) but nitrate uptake is also compromised, leading to reduced cellular levels of carbon, nitrogen and phosphorus (e.g., Takeda, 1998 and references therein). The release of nutrients, particularly iron, from melting sea-ice in spring is well-documented (e.g., Sedwick and DiTullio, 1997; Measures, 1999; Sambrotto et al., 2003), and as long as stratification is maintained, this can stimulate phytoplankton production in the melt-zone (e.g., De Baar et al., 1995; Sambrotto et al., 1986). Antarctic ice-core records show higher dust (iron, silica) content during cold periods over East Antarctica (e.g., Petit et al., 1999) particularly at the Last Glacial Maximum (LGM) and during the Ant-

arctic Cold Reversal (Delmonte et al., 2002). In the same way that increased dust to the oceans has been modelled to stimulate phytoplankton production during the LGM (e.g., Bopp et al., 2003), the release of ice-locked LGM dust by the melting ice-sheet during the deglacial, as well as that from seasonal sea-ice, may explain, in part, the exceptionally high spring diatom flux recorded in Iceberg Alley, particularly for the initial stages of ice-sheet melt. The retreating ice-sheet probably also created a calving bay re-entrant (Domack et al., 2003), which caused sediment focusing in Iceberg Alley and in other deeply incised basins on the MRS. As the ice-sheet retreated through the deglacial, primary production, and hence opal flux, decreased with time leading to a decrease in lamination thickness up-core (Fig. 3).

Although dust from ice melt can provide a source of iron and silica, it may not provide enough of the other nutrients, particularly phosphate and nitrate, to sustain the high diatom production recorded in JPC43B. Furthermore, Edwards and Sedwick (2001) suggest that upwelled iron is more important for high phytoplankton production in the Antarctic than that derived from seasonal sea-ice melt. For Iceberg Alley, an oceanic nutrient source derived south of the Polar Front is necessary in light of the absence of diatom taxa restricted to the north of the front. We suggest the relatively warm Upper CDW as a likely source, which may also contribute to elevated spring sea-surface temperatures and the break-up of pack ice (Jacobs et al., 1970). On the western Antarctic Peninsula, nutrient-rich, warm Upper CDW episodically upwells onto the shelf stimulating episodic diatom blooms (Prézelin et al., 2000). In East Antarctica, Rintoul (1998) demonstrates that modified Upper CDW impinges onto the shallow shelf in the Mertz Glacier Region and Sambrotto et al. (2003) suggest this water mass as a source for biologically utilisable iron for that region. It is also likely that modified Upper CDW could periodically intrude onto the MRS via deeply incised basins such as Iceberg Alley (Fig. 1) bringing with it the necessary nutrients to periodically (seasonally) stimulate high diatom productivity recorded in JPC43B.

In reality, both nutrient sources may have operated in Iceberg Alley at different times through the austral year. The *Chaetoceros* and *Corethron* blooms were rapidly stimulated by the initial spring sea-ice melt

which released nutrients including iron into the melt-zone. In late spring through summer an influx of warm Upper CDW brought a second nutrient supply rich in phosphate and nitrate as stratification started to break down and the mixed layer deepened. At the same time open water diatoms such as *Rhizosolenia* and the summer mixed assemblages were able to move into Iceberg Alley where they continued to reproduce before sea-ice reformation in late summer and autumn.

6. Summary

One hundred and ninety-two laminations are preserved in the lower ~2 m of the varved unit in core JPC43B (Iceberg Alley on the Mac.Robertson Shelf), an extraordinarily rich archive of climate and palaeoceanographic change with seasonal resolution. We described the diatom assemblages and microfabrics of these laminae and show that; (i) lamina couplets (varves) comprise thickly laminated to thinly bedded orange/orange-brown diatom-oozes and brown/blue-grey diatom-rich terrigenous laminae; (ii) the diatom oozes represent exceptionally high diatom production in the spring season comprising low-diversity *Hyalochaete Chaetoceros* spp. and *Corethron criophilum* oozes, with *Rhizosolenia antennata* f. *semispina* ($\pm$ *Proboscia inermis*) above ~23.41 mbsf; (iii) the terrigenous laminae represent the summer season comprising higher diversity, mixed diatom floras derived from the shelf or open (i.e., ice-free) water south of the Polar Front. Sub-laminae of *Thalassiosira antarctica* resting spores in the upper part of approximately a third of the summer laminae may indicate late summer or autumn; (iv) couplet pairs constitute a single austral year. Winter is represented by a single hiatus immediately below the successive spring lamination; (v) nutrients may have been derived locally from seasonal sea-ice melt, glacial ice-sheet melt and regionally from Upper Circumpolar Deep Water intruding onto the Mac.Robertson Shelf.

Acknowledgment

We thank Captain Joe Borkowski III and the crew of the *R/VIB Nathaniel B. Palmer* for their excellent

work during cruise NBP01-01, and Tom Janecek and Matt Curren of the Antarctic Research Facility (Florida State University) for their help with sampling and core photography. Thanks to two anonymous reviewers and Kelly Kryc for their helpful comments and suggestions for improvements to this paper. This work has been carried out under NERC grant NER/A/S/2001/01106 (Stickley and Pike) and NSF-OPP grants 9909367 (Leventer and McClenen), 9909837 (Dunbar), 9909803 (Brachfeld) and 9909793 (Manley).

References

- Abelmann, A., Gersonde, R., 1991. Biosiliceous particle flux in the Southern Ocean. *Marine Chemistry* 35, 503–536.
- Aletsee, L., Jahnke, J., 1992. Growth and productivity of the psychrophilic marine diatoms *Thalassiosira antarctica* Comber and *Nitzschia frigida* Grunow in batch cultures at temperatures below the freezing point of sea water. *Polar Biology* 11, 643–647.
- Allredge, A.L., Gotschalk, C.C., 1989. Direct observations of the mass flocculation of diatom blooms: characteristics, settling velocities and formation of diatom aggregates. *Deep-Sea Research* 36, 159–171.
- Allredge, A.L., Cowles, T.J., MacIntyre, S., Rines, J.E.B., Donaghay, P.L., Greenlaw, C.F., Holliday, D.V., Dekshenieks, M.M., Sullivan, J.M., Zaneveld, R.V., 2002. Occurrence and mechanisms of formation of a dramatic thin layer of marine snow in a shallow Pacific fjord. *Marine Ecology Progress Series* 233, 1–12.
- Armand, L., 2000. An ocean of ice—advances in the estimation of past sea ice in the Southern Ocean. *GSA Today*, vol. 10. Geological Society of America, pp. 1–7.
- Armand, L., Zielinski, U., 2001. Diatom species of the genus *Rhizosolenia* from Southern Ocean sediments: distribution and taxonomic notes. *Diatom Research* 16, 259–294.
- Bartsch, A., 1989. Die Eisalgenflora des Weddellmeeres (Antarktis): artenzusammensetzung und Biomasse sowie Ökophysiologie ausgewählter Arten. *Berichte Polarforschung* 63, 1–113.
- Bennett, K.D., Haberle, S.G., Lumley, S.H., 2000. The last Glacial-Holocene transition in Southern Chile. *Science* 290, 325–328.
- Blunier, T., Chappellaz, J., Schwander, J., Dällenbach, A., Stauffer, B., Stocker, T.F., Raynaud, D., Jouzel, J., Clausen, H.B., Hammer, C.U., Johnsen, S.J., 1998. Asynchrony of Antarctic and Greenland climate change during the last glacial period. *Nature* 394, 739–743.
- Bopp, L., Kohfeld, K.E., Le Quere, C., Aumont, O., 2003. Dust impact on marine biota and atmospheric CO₂ during glacial periods. *Paleoceanography* 18. doi:10.1029/2002PA000810.
- Boyd, P., et al., 2000. A mesoscale photoplankton bloom in the polar Southern Ocean stimulated by iron fertilization. *Nature* 407, 695–702.

- Boyle, E., 1998. Pumping iron makes thinner diatoms. *Nature*, 733–744.
- Broecker, W.S., 1998. Pecean circulation during the last deglaciation: a bipolar seesaw? *Paleoceanography* 13, 119–121.
- Broecker, W.S., Denton, G.H., 1989. The role of ocean-atmosphere reorganizations in glacial cycles. *Geochimica et Cosmochimica Acta* 53, 2465–2501.
- Burckle, L.H., Jacobs, S.S., McLaughlin, R.B., 1987. Late austral spring diatom distribution between New Zealand and the Ross Ice Shelf, Antarctica: hydrographic and sediment correlations. *Micropaleontology* 33, 74–81.
- Clarke, D.B., Ackley, S.F., Kumai, M., 1984. Morphology and ecology of diatoms in sea ice from the Weddell Sea. *Cold Regions Engineering and Laboratory Report* 84-5, 41 (February).
- Coale, K., et al., 1996. A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. *Nature* 383, 495–501.
- Crawford, R.M., Hinz, F., Rynearson, T., 1997. Spatial and temporal distribution of assemblages of the diatom *Corethron criophilum* in the Polar Frontal region of the South Atlantic. *Deep-Sea Research II* 44, 479–496.
- Crosta, X., Pichon, J.-J., Labracherie, M., 1997. Distribution of *Chaetoceros* resting spores in modern peri-Antarctic sediments. *Marine Micropaleontology* 29, 283–299.
- Crosta, X., Pichon, J.-J., Burckle, L.H., 1998a. Application of modern analog technique to marine Antarctic diatoms: reconstruction of maximum sea-ice extent at the Last Glacial Maximum. *Paleoceanography* 13, 284–297.
- Crosta, X., Pichon, J.-J., Burckle, L.H., 1998b. Reappraisal of Antarctic seasonal sea-ice at the Last Glacial Maximum. *Geophysical Research Letters* 25, 2703–2706.
- Cunningham, W., Leventer, A., 1998. Diatom assemblages in surface sediments of the Ross Sea: relationship to present oceanographic conditions. *Antarctic Science* 10, 134–146.
- Dean, J.M., Kemp, A.E.S., Bull, D., Pike, J., Patterson, G., Zolitschka, B., 1999. Taking varves to bits: scanning electron microscopy in the study of laminated sediments and varves. *Journal of Paleolimnology* 22, 121–136.
- De Baar, H.J.W., Jong, J.T.M., Bakker, D.C.E., Löscher, B.M., Veth, C., Bathmann, U., Smetacek, V., 1995. Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean. *Nature* 373, 412–415.
- Delmonte, B., Petit, J.R., Maggi, V., 2002. Glacial to Holocene implications of the new 27,000-year dust record from the EPICA Dome C (East Antarctica) ice core. *Climate Dynamics* 18, 647–660.
- Domack, E.W., 1988. Biogenic facies in the Antarctic glacimarine environment: basis for a polar glacimarine summary. *Palaeogeography Palaeoclimatology Palaeoecology* 63, 357–372.
- Domack, E.W., Leventer, A., Dunbar, R., Brachfeld, S., Manley, P., McClennen, C., 2003. Calving bay reentrants during the late Pleistocene to Holocene retreat of the Antarctic ice sheet: sedimentological and geomorphologic evidence. *Eos Transactions of AGU* 84 (46) (Fall Meet. Suppl., Abstract PP32D-07, 2003).
- Donegan, D., Schrader, H., 1972. Biogenic and abiogenic components of laminated hemipelagic sediments in the central Gulf of California. *Mar. Geol.* 48, 215–237.
- Doucette, G.J., Fryxell, G.A., 1985. *Thalassiosira antarctica* (Bacillariophyceae): vegetative and resting stage ultrastructure of an ice-related marine diatom. *Polar Biology* 4, 107–112.
- Duplessy, J.-C., Delibrias, G., Turon, J.L., Pujol, C., Duprat, J., 1981. Deglacial warming of the northeastern Atlantic ocean: correlation with the paleoclimatic evolution of the European continent. *Palaeogeography Palaeoclimatology Palaeoecology* 35, 121–144.
- Duplessy, J.-C., Arnold, M., Maurice, P., Bard, E., Duprat, J., Moyes, J., 1986. Direct dating of the oxygen-isotope record of the last deglaciation by ^{14}C accelerator mass spectrometry. *Nature* 320, 350–352.
- Edwards, R., Sedwick, P., 2001. Iron in East Antarctic snow: implications for atmospheric iron deposition and algal production in Antarctic waters. *Geophysical Research Letters* 28, 3907–3910.
- Fenner, J., Schrader, H.J., Weinigk, H., 1976. Diatom phytoplankton studies in the southern Pacific Ocean, composition and correlation to the Antarctic convergence and its paleoecological significance. *Initial Reports of the Deep Sea Drilling Project* 35, 757–813.
- Fryxell, G.A., 1989. Marine phytoplankton at the Weddell Sea ice edge: seasonal changes at the specific level. *Polar Biology* 10, 1–18.
- Fryxell, G.A., Hasle, G.R., 1971. *Corethron criophilum* Castracane: its distribution and structure. In: Llano, G.A., Wallen, I.E. (Eds.), *Biology of the Antarctic Seas IV*. American Geophysical Union, Antarctic Research Series, vol. 17, pp. 335–346.
- Fryxell, G.A., Doucette, G.J., Hubbard, G.F., 1981. The genus *Thalassiosira*: the bipolar diatom *T. antarctica* Comber. *Botanica Marina* 24, 321–335.
- Fryxell, G.A., Kang, S.-H., Reap, M.E., 1987. AMERIEZ 1986: phytoplankton at the Weddell Sea ice edge. *Antarctic Journal of the United States* 22, 173–175.
- General Bathymetric Chart of the Oceans (GEBCO): © Her Majesty in Right of Canada, 2000. Department of Fisheries and Oceans, Ottawa, Canada.
- Gleitz, M., Bartsch, A., Dieckmann, G.S., Eicken, H., 1998. Composition and succession of sea ice diatom assemblages in the eastern and southern Weddell Sea, Antarctica. In: Lizotte, M., Arrigo, K. (Eds.), *Antarctic Sea Ice Biological Processes, Interactions, and Variability*, Antarctic Research Series, American Geophysical Union, vol. 73, pp. 107–120.
- Gran, H.H., 1897. Bacillariaceen vom kleinen Karajakfjord. *Bibliotheca Botanica* 8, 13–24.
- Grimm, K.A., Lange, C.B., Gill, A.S., 1997. Self-sedimentation of phytoplankton blooms in the geologic record. *Sedimentary Geology* 110, 151–161.
- Guillard, R.L., Kilham, P., 1977. The ecology of marine planktonic diatoms, p. 372–469. In: Werner, D. (Ed.), *The Biology of Diatoms*. Botanical Monographs, vol. 13. Blackwell Scientific Publications, p. 498.
- Hargraves, P.E., French, F.W., 1975. Observations on the survival of diatom resting spores. *Beihefte zur Hedwigia* 53, 229–238.
- Hargraves, P.E., French, F., 1983. Diatom resting spores: significance and strategies. In: Fryxell, G.A. (Ed.), *Survival Strategies of the Algae*. Cambridge University Press, pp. 49–68.

- Harris, P.T., 2000. Ripple cross-laminated sediments on the East Antarctic Shelf: evidence for episodic bottom water production during the Holocene? *Marine Geology* 170, 317–330.
- Harris, P.T., O'Brien, P.E., 1996. Geomorphology and sedimentology of the continental shelf adjacent to Mac.Robertson Land, East Antarctica: a scalped shelf. *Geo-Marine Letters* 16, 287–296.
- Harris, P.T., O'Brien, P.E., 1998. Bottom currents, sedimentation and ice-sheet retreat facies successions on the Mac.Robertson shelf, East Antarctica. *Marine Geology* 151, 47–72.
- Hasle, G.R., 1976. The biogeography of some marine planktonic diatoms. *Deep-Sea Research* 23, 319–338.
- Hasle, G.R., Heimdal, B.R., 1968. Morphology and distribution of the marine centric diatom *Thalassiosira antarctica* Comber. *Journal of the Royal Microscopical Society* 88, 357–369.
- Heil, P., Allison, I., Lytle, V.I., 1996. Seasonal and interannual variations of the oceanic heat flux under a landfast Antarctic sea ice cover. *Journal of Geophysical Research* 101 (C11), 25741–25752.
- Hutchins, D.A., Bruland, K.W., 1998. Iron-limited diatom growth and Si:N uptake ratios in a coastal upwelling regime. *Nature* 393, 561–564.
- Jordan, R.W., Ligowski, R., Nöthig, E.-M., Priddle, J., 1991. The diatom genus *Proboscia* in Antarctic waters. *Diatom Research* 6, 63–78.
- Jacobs, S.S., 1989. Marine controls on modern sedimentation on the Antarctic continental shelf. *Marine Geology* 85, 121–153.
- Jacobs, S.S., Amos, A.F., Bruchhausen, P.M., 1970. Ross Sea oceanography and Antarctic Bottom Water formation. *Journal of Geophysical Research* 75, 935–962.
- Jouzel, J., Masson, V., Cattani, O., Falourd, S., Stievenard, M., Stenni, B., Longinelli, A., Johnsen, S.J., Steffensen, J.P., Petit, J.R., Schwander, J., Souchez, R., Barkov, N.I., 2001. A new 27 ky high resolution East Antarctic climate record. *Geophysical Research Letters* 28, 3199–3202.
- Kang, S.-H., Fryxell, G.A., 1992. *Fragilariopsis cylindrus* (Grunow) Krieger: the most abundant diatom in water column assemblages of Antarctic marginal ice-edge zones. *Polar Biology* 12, 609–627.
- Kemp, A.E.S., 1990. Sedimentary fabrics and variation in lamination style in Peru continental margin upwelling sediments. In: Suess, E., von Huene, R., et al. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 112, pp. 43–58.
- Kemp, A.E.S., Pearce, R.B., Pike, J., Marshall, J.E.A., 1998. Micro-fabric and microcompositional studies of Pliocene and Quaternary sapropels from the Eastern Mediterranean. In: Robertson, A.H.F., Emeis, K.-C., Richter, C., Camerlenghi, A. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 160, pp. 333–348.
- Knorr, G., Lohmann, G., 2003. Southern Ocean origin for the resumption of Atlantic thermohaline circulation during deglaciation. *Nature* 424, 532–536.
- Krinsley, D.H., Pye, K., Kearsley, A.T., 1983. Application of back-scattered electron microscopy in shale petrology. *Geological Magazine* 120, 109–114.
- Leventer, A., 1991. Sediment trap diatom assemblages from the northern Antarctic Peninsula region. *Deep Sea Research, Part A* 38, 1127–1143.
- Leventer, A., 1992. Modern distribution of diatoms in sediments from the George V Coast Antarctica. *Marine Micropaleontology* 19, 315–332.
- Leventer, A., 1998. The fate of Antarctic “sea-ice diatoms” and their use as paleoenvironmental indicators. In: Lizotte, M., Arrigo, K. (Eds.), *Antarctic Sea Ice Biological Processes, Interactions and Variability*. American Geophysical Union, Antarctic Research Series, vol. 73, pp. 121–137.
- Leventer, A., Dunbar, R.B., 1988. Recent diatom record of McMurdo Sound, Antarctica: implications for history of sea ice extent. *Paleoceanography* 3, 259–274.
- Leventer, A., Dunbar, R.B., DeMaster, D.J., 1993. Diatom evidence for late Holocene climatic events in Granite Harbor, Antarctica. *Paleoceanography* 8, 373–386.
- Leventer, A., Brachfeld, S., Domack, E., Dunbar, R., Manley, P., McClennen, C., Kryc, K., Beaman, R., Moy, A., Pike, J., Shevenell, A., Taylor, F., 2001. Preliminary Report on Cruise NBP01-01, East Antarctic Margin. *Eos Transactions of AGU* 82 (47) (Fall Meet. Suppl., Abstract PP51A-0535, 2001).
- Leventer, A., Domack, E., Barkoukis, A., McAndrews, B., Murray, J., 2002. Laminations from the Palmer Deep: a diatom-based interpretation. *Paleoceanography* 17, 1–15.
- Leventer, A., Brachfeld, S., Domack, E., Dunbar, R., Manley, P., McClennen, C., Pike, J., Maddison, E., Stickley, C., Taylor, F., 2003. Sedimentary Laminations in the Southern Ocean: Production, concentration and preservation of bloom events. Abstract for Chapman Conference 2003 on *The Role of Diatom Production and Si Flux and Burial in the Regulation of Global Cycles*. Paroikia, Paros, Greece 22–26 September 2003.
- Ligowski, R., Godlewski, M., Lukowski, A., 1992. Sea ice diatoms and ice edge planktonic diatoms at the northern limit of the Weddell Sea pack ice. *Proceedings of the NIPR Symposium on Polar Biology* 5, 9–20.
- Maddison, E.J., Pike, J., Leventer, A., Domack, E.W. in press. Diatom-rich sediments from Palmer Deep, Antarctica: Seasonal and sub-seasonal record through the last deglaciation. *Journal of Quaternary Science*.
- Martin, J.H., Fitzwater, S.E., 1988. Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic. *Nature* 331, 341–343.
- McMinn, A., Heijnis, H., Harle, K., McOrist, G., 2001. Late-Holocene climate change recorded in sediment cores from Ellis Fjord, eastern Antarctica. *The Holocene* 11, 291–300.
- Measures, C.I., 1999. The role of entrained sediments in sea ice in the distribution of aluminium and iron in the surface waters of the Arctic Ocean. *Marine Chemistry* 68, 59–70.
- Mix, A.C., Ruddiman, W.F., 1985. Structure and timing of the last deglaciation: oxygen isotope evidence. *Quaternary Science Reviews* 4, 59–108.
- Morgan, V., Delmotte, M., van Ommen, T., Jouzel, J., Chappellaz, J., Woon, S., Masson-Delmotte, V., Raynaud, D., 2002. Relative timing of deglacial climate events in Antarctica and Greenland. *Science* 297, 1862–1864.

- O'Brien, P.E., Truswell, E.M., Burton, T., 1994. Morphology, seismic stratigraphy and sedimentary history of the Mac.Robertson shelf, East Antarctica. *Terra Antarctica* 1, 407–408.
- Orsi, A.H., Johnson, G.C., Bullister, J.L., 1999. Circulation, mixing, and production of Antarctic Bottom Water. *Progress in Oceanography* 45, 55–109.
- Palmisano, A.C., Garrison, D.L., 1993. Microorganisms in Antarctic sea ice, p. 167–218. In: Friedmann, I.E. (Ed.), *Antarctic Microbiology*. John Wiley and Sons, p. 634.
- Peters, E., Thomas, D.N., 1996. Prolonged darkness and diatom mortality: I. Marine Antarctic species. *Journal of Experimental Marine Biology and Ecology* 207, 25–41.
- Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Benders, M., Chappellaz, J., Davis, M., Delaygue, G., Delmonte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pépin, L., Ritz, C., Saltman, E., Stievenard, M., 1999. Climatic and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* 399, 429–436.
- Pike, J., Kemp, A.E.S., 1996. Preparation and analysis techniques for studies of laminated sediments. In: Kemp, A.E.S. (Ed.), *Palaeoclimatology and Palaeoceanography from Laminated Sediments*. Special Publication-Geological Society of London, vol. 116, pp. 37–48.
- Pike, J., Moreton, S.G., Allen, C.A., 2001. Data report: Microfabric analysis of postglacial sediments from Palmer Deep, Western Antarctic Peninsula. In: Barker, P.F., Camerlenghi, A., Acton, G.D., Ramsay, A.T.S. (Eds.), *Proc. ODP, Sci. Res.*, vol. 178, pp. 1–17 [online]. Available from World Wide Web: http://www-odp.tamu.edu/publications/178_SR/VOLUME/CHAPTERS/SR178_18.PDF [Cited 2005-April 9].
- Prézelin, B.B., Hofmann, E.E., Mengelt, C., Klink, J.M., 2000. The linkage between Upper Circumpolar Deep Water (UCDW) and phytoplankton assemblages on the west Antarctic Peninsula continental shelf. *Journal of Marine Research* 58, 165–202.
- Renssen, H., Isarin, R.F.B., Vandenbergh, J., workshop participants, 2001. Rapid climatic warming at the end of the last glacial: new perspectives. *Global and Planetary Change* 30, 155–165.
- Rintoul, S.R., 1998. On the origin and influence of Adelie Land bottom water. In: Jacobs, S.S. (Ed.), *Ocean, Ice and Atmosphere: Interactions at the Antarctic Continental Margin*. American Geophysical Union, Antarctic Research Series, vol. 75, pp. 151–171.
- Rintoul, S.R., Bullister, J.L., 1999. A late winter hydrographic section from Tasmania to Antarctica. *Deep Sea Research I* 46, 1417–1454.
- Sambrotto, R.N., Niebauer, H.J., Goering, J.J., Iverson, R.L., 1986. The relationship among vertical mixing, nitrate uptake, and growth during the spring phytoplankton bloom in the southeast Bering Sea middle shelf. *Continental Shelf Research* 5, 161–198.
- Sambrotto, R.N., Matsuda, A., Vaillancourt, R., Brown, M., Langdon, C., Jacobs, S.S., Measures, C., 2003. Summer plankton production and nutrient consumption patterns in the Mertz Glacier Region of East Antarctica. *Deep-Sea Research II* 50, 1393–1414.
- Schimmelmann, A., Lange, C.B., Berger, W.H., 1990. Climatically controlled marker layers in Santa Barbara Basin sediments and fine-scale core-to-core correlation. *Limnology and Oceanography* 35, 165–173.
- Schuette, G., Schrader, H., 1979. Diatom taphocoenoses in the coastal upwelling area off western Southern America. *Nova Hedwigia* 64, 359–378.
- Sedwick, P.N., DiTullio, G.R., 1997. Regulation of algal blooms in Antarctic shelf waters by the release of iron from melting sea ice. *Geophysical Research Letters* 24, 2515–2518.
- Sedwick, P.N., Harris, P.T., Robertson, L.G., McMurtry, G.M., Cremer, M.D., Robinson, P., 1998. A geochemical study of marine sediments from the Mac.Robertson Shelf, East Antarctica: initial results and palaeoenvironmental implications. *Annals of Glaciology* 27, 268–274.
- Sedwick, P.N., Harris, P.T., Robertson, L.G., McMurtry, G.M., Cremer, M.D., Robinson, P., 2001. Holocene sediment records from the continental shelf of Mac.Robertson Land, East Antarctica. *Paleoceanography* 16, 212–225.
- Shemesh, A., Hodell, D., Crosta, X., Kanfoush, S., Charles, C., Guilderson, T., 2002. Sequence of events during the last deglaciation in Southern Ocean sediments and Antarctic ice cores. *Paleoceanography* 17, 1056–1063.
- Smith, N.R., Zhaoqian, D., Wright, S., 1984. Water masses and circulation in the region of Prydz Bay, Antarctica. *Deep Sea Research* 31, 1121–1147.
- Stockwell, D.A., 1991. Distribution of *Chaetoceros* resting spores in the Quaternary sediments from Leg 119. *Proceedings of the Ocean Drilling Program. Scientific Results* 119, 599–610.
- Syvrtsen, E.E., 1979. Resting spore formation in clonal cultures of *Thalassiosira antarctica* Comber, *T. nordenskiöldii* Cleve and *Denotula confervaeae* (Clev.) Gran. *Nova Hedwigia. Beiheft* 64, 41–64.
- Takeda, S., 1998. Influence of iron availability on nutrient consumption ratio of diatoms in oceanic waters. *Nature*, 774–777.
- Taylor, F., McMin, A., Franklin, D., 1997. Distribution of diatoms in surface sediments of Prydz Bay, Antarctica. *Marine Micro-paleontology* 32, 209–229.
- Taylor, F., McMin, A., 2001. Evidence from diatoms for Holocene climate fluctuation along the East Antarctic Margin. *The Holocene* 11, 455–466.
- Truesdale, R.S., Kellogg, T.B., 1979. Ross Sea diatoms: modern assemblage distributions and their relationship to ecologic, oceanographic, and sedimentary conditions. *Marine Micropaleontology* 4, 13–31.
- Villareal, T.A., Fryxell, G.A., 1983. Temperature effects on the valve structure of the bipolar diatoms *Thalassiosira antarctica* and *Porosira glacialis*. *Polar Biology* 2, 163–169.
- Whitworth III, T., Orsi, A.H., Kim, S.-J., Nowlin Jr., W.D., Locarnini, R.A., 1998. Water masses and mixing near the Antarctic slope front. In: Jacobs, S.J., Weiss, R.F. (Eds.), *Ocean, Ice, and Atmosphere: Interactions at the Antarctic Continental Margin*. American Geophysical Union, Antarctic Research Series, vol. 75, pp. 1–27.
- Zielinski, U., Gersonde, R., 1997. Diatom distribution in Southern Ocean surface sediments (Atlantic Sector): implications for paleoenvironmental reconstructions. *Palaeogeography Palaeoclimatology Palaeoecology* 129, 213–250.