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Post-glacial seasonal diatom record of the Mertz Glacier Polynya, East Antarctica

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Abstract

An ultra-high-resolution post-glacial laminated sediment record from Mertz Ninnis Trough, East Antarctic Margin (EAM), has been analysed using SEM backscattered electron imagery, secondary electron imagery and quantitative diatom abundance. Laminations are classified using visually dominant diatom species and terrigenous content. Four biogenic diatom ooze laminae types, one diatom-bearing terrigenous lamina type and one diatom-bearing terrigenous sub-lamina type have been identified. Diatom ooze lamina types comprise near-monogeneric *Hyalochaete Chaetoceros* spp. resting spore laminae, laminae characterised by *Corethron pennatum*, laminae characterised by *Rhizosolenia* spp. and mixed diatom assemblage laminae. Diatom-bearing terrigenous lamina and sub-lamina types comprise mixed diatom assemblage terrigenous laminae and sub-laminae characterised by *Porosira glacialis* resting spores. Formation of each of these lamina types is controlled by seasonal changes in nutrients, oceanographic regimes and the Mertz Glacier Polynya dynamics.

Keywords: Mertz Ninnis Trough; Mertz Glacier Polynya; seasonality; diatoms; laminated; East Antarctica

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1. Introduction

Ultra-high-resolution diatom-rich laminated records from Antarctica have been studied to provide information on past climatic and oceanographic behaviour during periods of rapid climate change e.g. Palmer Deep, Antarctic Peninsula (Leventer et al., 2002; Maddison et al., 2005) and Iceberg Alley on Mac. Robertson Shelf (Stickley et al., 2005). These diatom-rich laminated sediments are all retrieved from deep inner shelf depressions and have very high sedimentation rates and extremely good diatom frustule preservation. These investigations have revealed annual sedimentary records.

Previously, modern (Leventer, 1992) and Holocene (Escutia et al., 2003) diatom assemblages have been examined in the Mertz Ninnis Trough region. Analyses of surface sediment diatom assemblages were conducted in this region to correlate the modern distribution of diatoms with specific climatic and environmental variables (Leventer, 1992). The modern distribution of *Fragilariopsis curta* and *F. kerguelensis* in surface sediments displayed the potential of these two species to help track sea ice retreat across the continental shelf during the Holocene (Leventer, 1992). The distribution of *Thalassiosira* spp. in surface sediments were determined to be associated with areas of open water productivity (Leventer, 1992). Quantitative diatom assemblage analyses of Holocene laminated sediments indicate that in this region sea ice conditions fluctuated with periodicities at the century scale (Escutia et al., 2003).

In this study a well-laminated, diatom-rich Holocene sedimentary sequence from Mertz Ninnis Trough, situated along the George V Coast (Fig. 1) on the East Antarctic Margin, is analysed in detail using Scanning Electron Microscope (SEM) methods. Several types of laminae are described and processes responsible for lamina formation are explored. Antarctic laminated sediments from similar settings have previously been suggested to represent annual deposition (e.g. Leventer et al., 2002) hence, the Mertz Ninnis Trough laminated

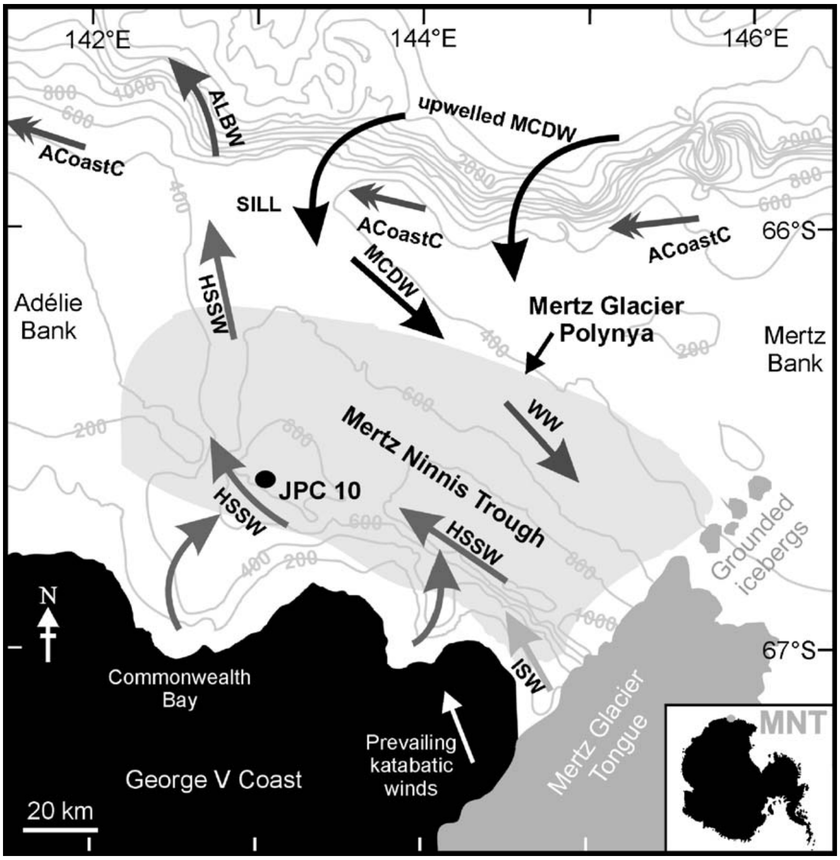


Fig. 1. Oceanographic regime of the George V Coast (modified from Harris et al., 2001). ACoastC = Antarctic Coastal Current. MCDW = Modified Circumpolar Deepwater. HSSW = High Salinity Shelf Water. ISW = Ice Shelf Water. WW = Winter Water. ALBW = Adélie Land Bottom Water. The position of the core NBP01-01 JPC10 is indicated. Inset is the location of the Mertz Ninnis Trough (MNT) on the East Antarctic Margin.

sediments will be assessed for annual cyclicity by examining sequences of diatom assemblages and lamina relationships.

Oceanic bottom water is formed on this part of the George V Coast and this region is the second largest contributor to Antarctic Bottom Water (AABW), contributing 25% of the total AABW volume in the world's ocean (Rintoul, 1998). Hence, the Mertz Ninnis Trough laminated sediments should provide a unique insight into the past dynamics of this oceanographically significant region.

1.1. Regional setting

The Mertz Ninnis Trough [also known as the George V Basin (Domack, 1982; Domack and Anderson, 1983; Leventer, 1992; Harris et al., 2001; Harris and Beaman, 2003; Presti et al., 2003) and the Adélie Depression (Gordon and Tchernia, 1972; Rintoul, 1998)] is a glacially formed depression on the East Antarctic inner continental shelf which reaches depths greater than 1300 m just east of the Mertz Glacier Tongue (Fig. 1). Adjacent to the Mertz Ninnis Trough are two broad, relatively shallow linear banks, the Mertz and Adélie Banks (200 to 400 m deep) (Fig. 1). To the east of the trough are two actively expanding and contracting glacier tongues, the Mertz (Fig. 1) and Ninnis Glacier Tongues (Wendler et al., 1996). Sediment-laden icebergs calve from these two glacier tongues and drift westward due to the Antarctic Coastal Current (Domack and Anderson, 1983).

Katabatic winds in this region are some of the strongest and most persistent winds on earth. The strongest and most frequent katabatic winds occur during the austral winter (Périard and Pettré, 1993). A 30% decrease in mean wind speed (Périard and Pettré, 1993) and an increase in daily insolation between austral winter and summer months means that less water column mixing occurs in the summer. Katabatic winds mechanically force sea ice away from the shore and the western edge of the Mertz Glacier Tongue (Adolphs and Wendler, 1995; Wendler et al., 1997; Massom et al., 2001). This, combined with the deflection of westward moving sea ice by the Mertz Glacier Tongue (Massom et al., 2001) allows a coastal polynya, the Mertz Glacier Polynya, to form (Fig. 1). Coastal polynyas are known as "ice factories" and have large sea ice formation rates, which can be up to ten times greater than in the surrounding sea ice zone (Zwally et al., 1985). The ice formation rates depend on local wind speed, air and water temperature and the area of open water (function of wind speed and persistence) (Cavalieri and Martin, 1985; Zwally et al., 1985). The Mertz Glacier Polynya is a persistent, recurrent feature throughout the year (Massom et al., 1998) and is believed to have the greatest ice production and therefore, highest rate of salt production in East Antarctica (Cavalieri and Martin, 1985). The fastest rate of areal growth of the polynya occurs during August/September (Bindoff et al., 2001) and multi-year special sensor microwave/imager records have shown that the polynya typically attains its largest size in October (20000 to 60000 km^2), at the approximate time of maximum pack ice extent.

Oceanography off the George V Coast is dominated by the upwelling of Modified Circumpolar Deepwater (MCDW) due to the northerly extent of the coastline and the proximity of the warm, saline waters to the shelf break (Orsi et al., 1995). MCDW appears to enter the Mertz Ninnis Trough through a U-shaped sill near 143°E (Fig. 1), connecting the depression to deep water offshore (Rintoul, 1998). Upwelling of warm MCDW, a source of sensible heat over the continental shelf, may help to maintain the Mertz Glacier Polynya and explain the temporal development of the polynya through the winter (Rintoul, 1998). In austral spring/summer (October–March) waters inside the polynya absorb solar radiation, melting sea ice (Hunke and Ackley, 2001; Ohshima et al., 1998). The resultant freshwater cap overlies the MCDW reservoir of sensible heat. The combination of enhanced melting and narrow sea ice zone allows an ice edge embayment to merge with the Mertz Glacier Polynya, forming a large region with reduced ice concentrations reaching the coast in austral summer (December) (Massom et al., 1998). MCDW cannot reach the surface of the polynya until sufficient cooling and brine formation has occurred to increase the density of the surface layer to equal that of the MCDW (Rintoul, 1998). MCDW becomes Winter Water (weakly stratified water <500 m water depth) as a result of atmospheric cooling and brine rejection in the polynya. High Salinity Shelf Water is also formed by brine rejection during sea ice formation and accumulates below Winter Water. Adélie Land Bottom Water (ALBW) is formed from the combination of High Salinity Shelf Water and Winter Water, and spills over the sill off the shelf (Bindoff et al., 2001).

In Antarctic shelf waters diatom growth is influenced by light levels, the extent of sea ice cover, water column stability (Mitchell et al., 1991; Nelson and Smith, 1991) and nutrient levels in the water column. In coastal polynyas, phytoplankton productivity commences soon after the spring equinox, allowing a longer growing season relative to shelf areas extensively covered in sea ice (Sambrotto et al., 2003). Primary productivity is high

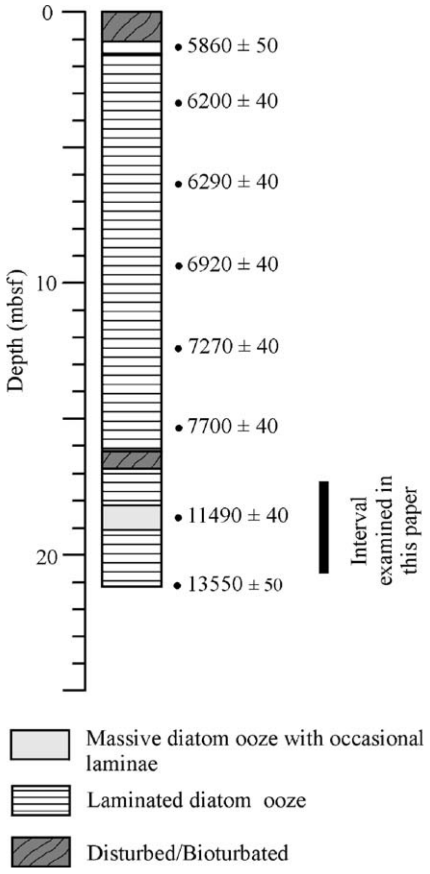


Fig. 2. Stratigraphic column of NBP01-01 JPC10, Mertz Ninnis Trough. Ages are uncorrected. Sampled interval, 17.36–20.60 mbsf (metres below sea floor), is marked.

along marginal ice zones (Smith and Nelson, 1986; Legendre et al., 1992), 4–5 times greater than productivity under sea ice (Burckle et al., 1987). Sea ice melt-induced water column stratification induces elevated diatom growth (Sambrotto et al., 1986; Arrigo et al., 1998). In the Mertz Ninnis Trough region katabatic winds periodically mix surface waters, destroying stratification, redistributing nutrients to surface waters. There are several possible sources of the essential micronutrient iron to this region. The intrusion of MCDW onto the shelf replenishes depleted iron pools (Sambrotto et al., 2003), re-suspension of shelf sediments is thought to be a source of dissolved and particulate iron (Fitzwater et al., 2000; Sedwick et al., 2000) and iron is derived from glacial scour associated with the Mertz Glacier Tongue (Vaillancourt et al., 2003). The melting of pack ice and snow pack is not thought to be a major source of iron to surface waters (Edwards and Sedwick, 2001; Vaillancourt et al., 2003).

It is essential to understand the George V Coast environment since the existence of the Mertz Glacier Polynya is believed to be vital for the formation of ALBW (Fukamachi et al., 2000). The rise in temperatures recorded in this region over the last three decades (Wendler and Prichard, 1991; Périard and Pettré, 1993) indicates that this area is sensitive to current climate change therefore, any climatic change-induced effect on the existence of the polynya could have consequences for the global thermohaline circulation. This investigation of the diatom-rich laminated sediments from the Mertz Ninnis Trough will provide a high resolution record of the behaviour of the Mertz Glacier Polynya during the early Holocene, hence contribute to our understanding of the past oceanography and environment of this important region.

2. Materials and methods

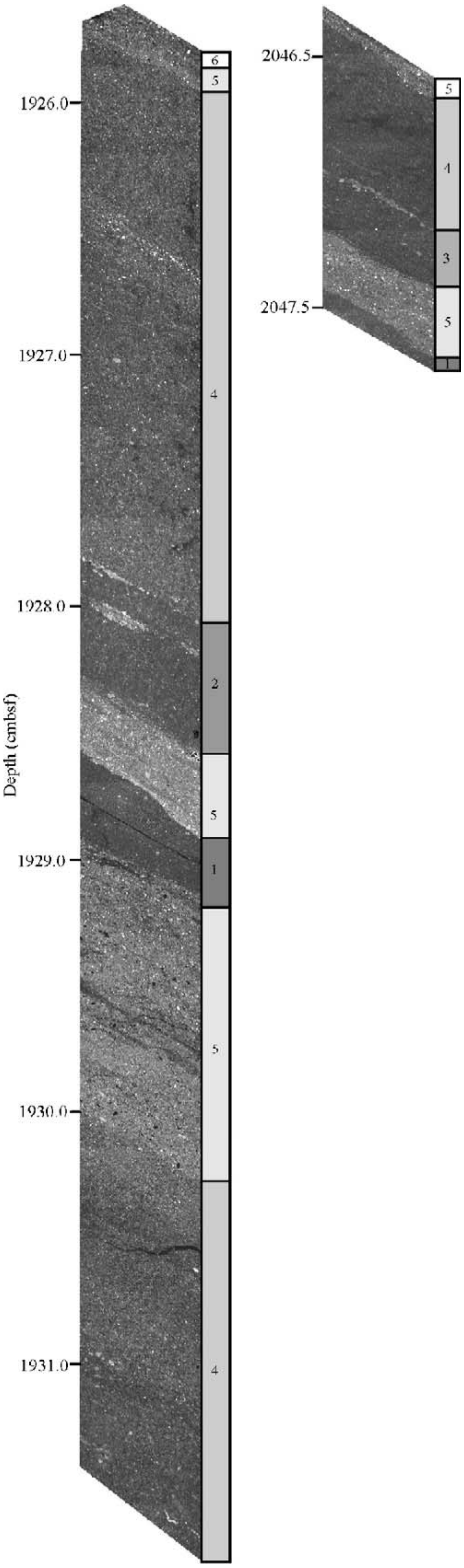
In 2001, cruise NBP01-01 of the *RVIB Nathaniel B. Palmer* recovered a 21.35 m diatomaceous marine sediment jumbo piston core, JPC10, from the Mertz Ninnis Trough, just off the George V Coast, East Antarctica (66° 34.334′S, 143° 05.168′E; water depth of 850 m) (Fig. 1). Throughout much of its length, the core is laminated, with minor amounts of bioturbation (Leventer et al., 2001) (Fig. 2).

Eight AMS radiocarbon ages were obtained from NBP01-01 JPC 10 to provide the core chronology (Table 1). Radiocarbon dating is complicated in the Antarctic as a result of unusually low radiocarbon (^{14}C) in Antarctic waters. Living organic material has been found to yield anomalously old ^{14}C ages (Andrews et al., 1999; Harris, 2000; Pudsey and Evans, 2001), a phenomenon called the Antarctic reservoir effect, therefore, measured radiocarbon ages are corrected to account for this effect. Reworking of old carbon is also a concern when interpreting ^{14}C ages in the Antarctic.

Table 1
Radiocarbon ages for core NBP01-01 JPC 10

CAMS lab #	Depth (mbsf)	^{14}C yr	±	Carbon source
79274	1.33	5860	50	Decal. C_{org}
79276	3.33	6200	40	Decal. C_{org}
79277	6.33	6290	40	Decal. C_{org}
79278	9.35	6920	40	Decal. C_{org}
79279	12.43	7270	40	Decal. C_{org}
79280	15.53	7700	40	Decal. C_{org}
79282	18.53	11,490	40	Decal. C_{org}
79283	21.13	13,550	50	Decal. C_{org}

mbsf = metres below sea floor. Decal. C_{org} = decalcified organic carbon.



In cores from the George V Coast, due to concerns about variable amounts of reworked material downcore, we have chosen to present uncorrected and uncalibrated radiocarbon ages. A local surface sediment radiocarbon age, 2340 ^{14}C yr (0–2 cm below sea floor), was obtained from NBP01-01 KC10A (66°34.328′S, 143°05.249′E, water depth of 850 m).

Core JPC10 was sampled with a sediment slab cutter (Schimmelmann, 1990) between 17.36 to 20.60 m below sea floor (mbsf) (13267–9809 ^{14}C yr). This interval samples the earliest well-laminated sedimentary record at this site. A total of nineteen sediment slabs were collected (from the intervals 17.36–17.65, 17.71–18.20, 18.72–18.91, 19.09–19.97, and 20.09–20.60 mbsf) and were kept cold and moist to prevent sample desiccation. These slabs were sub-sampled perpendicular to the laminations for polished thin section preparation and parallel to the laminations for scanning electron microscope (SEM) stub preparation (Pike and Kemp, 1996; Dean et al., 1999).

Polished thin sections of the sediment were prepared using a fluid displacive embedding technique (Pike and Kemp, 1996; Pearce et al., 1998). Using backscattered electron imagery (BSEI) on a Cambridge Instruments (LEO) S360 SEM, consecutive low-magnification images (×20) were taken of each thin section to produce a mosaic (Fig. 3). Using the mosaic as a map, inspection of the laminae at higher magnification (×100–1000) allowed qualitative analysis of the main diatom species present within the laminae (Fig. 4). The mosaics and higher magnification images were used together to determine lamina diatom assemblage composition and the sedimentary fabric (Pike and Kemp, 1996).

Sediment blocks were cut from the sediment slabs and fractured within laminae to reveal surfaces parallel to the laminated sediment fabric. The sediment blocks were mounted on standard SEM stubs, left to dry for 24 h and coated in Au–Pd (90:10) for topographic secondary electron imagery (SEI) analysis using a Veeco FEI (Philips) XL30 Environmental Scanning Electron Microscope (ESEM) with a FEG (Field

Fig. 3. Backscattered electron imagery (BSEI) photomosaics of diatom ooze laminae (Dark: Lamina types 1–4) and diatom-bearing terrigenous laminae (Light: Lamina and sub-lamina types 5 and 6). 1 = near-monogeneric *Hyalochaete Chaetoceros* spp. resting spore biogenic laminae. 2 = biogenic laminae characterised by *Corethron pennatum*. 3 = biogenic laminae characterised by *Rhizosolenia* spp. 4 = mixed diatom assemblage biogenic laminae. 5 = mixed diatom assemblage terrigenous laminae. 6 = terrigenous sub-laminae characterised by *Porosira glacialis* resting spores. cmbsf = centimetres below sea floor.

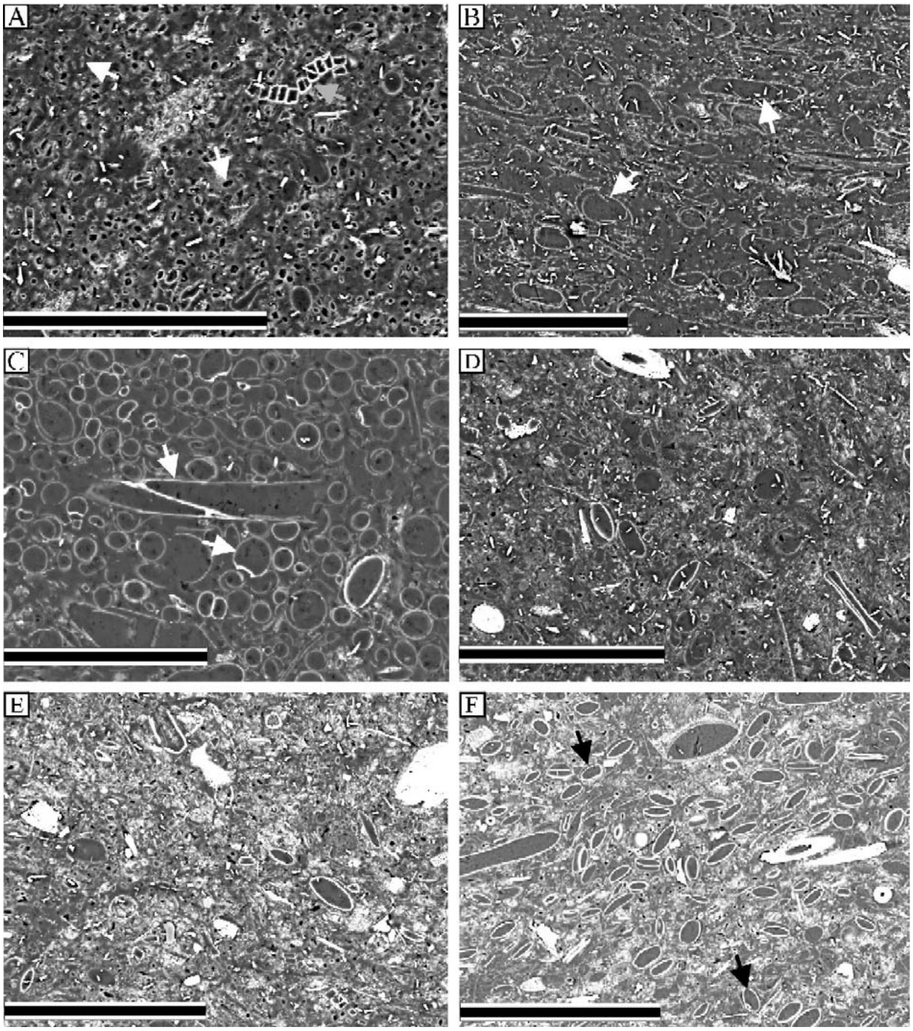


Fig. 4. Backscattered electron imagery (BSEI) photographs. (A) Lamina Type 1. Near-monogeneric *Hyalochaete Chaetoceros* spp. resting spore (white arrows) biogenic laminae. Scale bar = 200 μm. Grey arrow indicates a chain of *Fragilariopsis* spp. (B) Lamina Type 2. Biogenic laminae characterised by *Corethron pennatum* (white arrows). Scale bar = 200 μm. (C) Lamina Type 3. Biogenic laminae characterised by *Rhizosolenia* spp. (white arrows). Scale bar = 60 μm. (D) Lamina Type 4. Mixed diatom assemblage biogenic laminae. Scale bar = 200 μm. (E) Lamina Type 5. Mixed diatom assemblage terrigenous laminae. Scale bar = 200 μm. (F) Sub-lamina Type 6. Terrigenous sub-laminae characterised by *Porosira glacialis* resting spores (black arrows). Scale bar = 300 μm.

Emission Gun). SEI analysis was used to assist diatom species identification.

Quantitative slides were made to analyse diatom assemblages and species abundance in selected laminae or sub-laminae. The slides were prepared using the settling technique described in Scherer (1994) and fixed with Norland optical adhesive (Refractive Index 1.56). A minimum of 400 valves were counted per slide using an Olympus BX40 microscope with phase contrast, at ×1000. *Hyalochaete Chaetoceros* spp. resting spores (CRS) dominate the diatom assemblage therefore two separate counts per slide are made, a total species count (Table 2) and a CRS free count (Table 3). The CRS free counts allow trends of less common but ecologically important species to be revealed (Leventer et al., 1996). Relative abundances were calculated as a percentage of the total diatom assemblage and absolute abundances (valves per gram of dry sediment) as detailed in Scherer (1994). Diatom taxonomic identification in this study follows Hasle and Syvertsen (1997). For more taxonomic detail on *Proboscia* spp., *Rhizosolenia* spp. and *Thalassiosira* spp., Jordan et al. (1991), Armand and Zielinski (2001), and Johansen and Fryxell (1985) were used, respectively. *Rhizosolenia* species A (Armand and Zielinski, 2001) is re-identified as *R. simplex* (L. Armand, personal communication, 2006).

Table 2
Quantitative diatom abundance counts, all species

Species	Depth (mbsf)	18.898	18.908	18.894	20.23	18.77	20.39	19.58	17.9	17.88	19.72	19.2	20.47	19.215	18.875	20.157
	Number of FOV	7.5	2	3.5	7	4	30	7	10	9	8	8	14.5	20	5	7
	Mass (g)	0.0066	0.0053	0.005	0.0067	0.006	0.0066	0.006	0.0059	0.006	0.0069	0.0058	0.0056	0.0061	0.007	0.0055
	Lamina type	LT1	LT1	LT1	LT1	LT1	LT2	LT2	LT2	LT2	LT2	LT3	LT3	LT3	LT3	LT3
Actinocyclus actinochilus (Ehrenberg) Simonsen		0	0	0	0	1	0	0	0	0	2	1	0	0	0	0
Actinocyclus curvatulus Janisch in Schmidt		0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Asteromphalus spp. (Ehrenberg)		0	0	0	0	0	2	0	0	0	0	0	0	1	0	1
Corethron pennatum (Grunow) Ostenfeld		0	0	1	0	0	32	11	46	35	21	0	6	0	0	0
Coscinodiscus spp. Ehrenberg		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eucampia antarctica (Castracane) Mangin		1	0	0	2	0	0	1	0	0	1	0	1	6	0	0
Fragilariopsis curta (Van Heurck) Hustedt		20	4	8	7	7	29	10	14	19	15	4	29	24	8	2
Fragilariopsis cylindrus (Grunow) Krieger		1	0	5	0	4	2	10	24	27	7	0	33	34	11	4
Fragilariopsis cylindriformis (Hasle) Hasle		0	0	1	0	0	0	0	0	0	0	0	10	0	1	0
Fragilariopsis kerguelensis (O'Meara) Hustedt		11	0	3	2	5	5	1	3	0	2	8	5	1	2	4
Fragilariopsis obliquecostata (Van Heurck) Heiden		0	1	1	2	0	0	0	0	0	0	1	0	1	0	0
Fragilariopsis pseudonana (Hasle) Hasle		0	0	0	0	0	0	2	1	0	0	0	3	0	0	0
Fragilariopsis rhombica (O'Meara) Hustedt		12	1	2	3	1	9	2	6	2	14	9	19	21	8	6
Fragilariopsis ritscheri (Hustedt) Hasle		0	0	0	0	0	2	0	0	0	2	2	0	1	0	1
Fragilariopsis separanda Hustedt		9	0	4	0	1	3	0	0	1	0	0	23	2	1	1
Fragilariopsis sublinearis (Van Heurck) Heiden		0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
Fragilariopsis vanheurckii (M. Pergallo) Hustedt		0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Fragilariopsis spp. Hustedt		6	0	2	0	0	1	0	0	0	0	0	0	0	0	0
Hyalochaete Chaetoceros spp. (vegetative) Gran		8	0	4	10	15	19	4	3	4	7	1	5	14	6	2
Hyalochaete Chaetoceros spp. (resting spore) Gran		318	438	364	402	435	301	375	326	332	329	416	251	256	407	442
Navicula spp. Bory de St-Vincent		1	0	1	0	0	0	1	0	0	0	0	0	1	0	0
Phaeoceros Chaetoceros spp. Gran		4	0	1	0	0	0	0	4	6	3	4	1	3	2	2
Porosira glacialis (Grunow) Jørgensen		0	1	1	2	1	1	1	0	0	0	0	1	2	1	0
Proboscia inermis (Castracane) Jordan and Ligowski		0	0	0	0	0	0	0	0	1	0	1	1	5	0	1
Proboscia truncata (Karsten) Nöthig and Ligowski		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Pseudo-nitzschia turgidula (Hustedt) Hasle		1	0	1	0	0.5	0	2	3	0	3	0.5	3	4.5	4	0
Rhizosolenia antennata f. *semispina* Sundström		0	0	2	1	1	1	2	0	0	0	2	1	23	3	1
Rhizosolenia polydactyla Castracane f. *polydactyla*		0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
Rhizosolenia simplex Karsten		1	0	0	0	0	0	0	0	0	1	2	1	8	0	1
Rhizosolenia spp. Brightwell		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassiosira antarctica (resting spore) Comber		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassiosira gracilis v. *expecta* (Van Landingham) Fryxell and Hasle		0	0	0	1	0	1	0	0	0	0	0	1	0	1	0
Thalassiosira gracilis v. gracilis (Karsten) Hustedt		1	0	0	3	0	3	1	0	1	0	1	3	0	1	0
Thalassiosira gravida Cleve		1	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Thalassiosira lentiginosa (Janisch) Fryxell		0	1	0	0	0	2	1	0	0	1	0	0	6	1	0
Thalassiosira lineata Jousé		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Thalassiosira oestrupii (Ostenfeld) Hasle		0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Thalassiosira poroseriata (Ramsfjell) Hasle		0	0	0	5	0	0	1	0	0	0	0	0	0	0	0
Thalassiosira ritscheri (Hustedt) Hasle		0	0	0	1	0	0	0	0	0	0	0	0	2	0	0
Thalassiosira tumida (Janisch) Hasle		0	0	0	0	0	1	0	0	0	0	1	0	2	0	0
Thalassiosira spp. Cleve		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Thalassiothrix antarctica Schimper ex Karsten		0.5	0	0	0	0	1	0	0.5	0.5	0	0	0	0	0	0
Trichotoxon reinboldii (Van Heurck) Reid and Round		2.5	0	0	0	0	1	0.5	0	0	0	0.5	0	0.5	0	0
Unidentified centrics		0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Unidentified pennates		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Total		400	446	402	442	471.5	417	425.5	430.5	428.5	409	454	400	423	459	468

FOV = Field of View. mbsf = metres below sea floor. LT = Lamina Type.

19.31	19.521	19.74	20.466	20.54	18.9	18.889	18.887	19.36	19.96	19.528	19.536	19.716	19.536	20.586
6	3	8	16	5	4	5	5	6	12	2.5	3	7	2	6
0.0051	0.0068	0.0051	0.0056	0.0059	0.008	0.0093	0.0093	0.0095	0.0081	0.0083	0.007	0.0097	0.0067	0.0085
LT4	LT4	LT4	LT4	LT4	LT5	LT5	LT5	LT5	LT5	LT6	LT6	LT6	LT6	LT6
0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	1	0	0	0	0	0	1	0
3	1	4	1	0	0	0	1	3	0	0	1	2	0	0
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
1	1	2	0	0	1	0	0	2	0	0	1	0	0	1
33	3	20	29	16	21	33	10	13	13	2	1	15	0	9
14	1	3	45	4	3	4	5	5	11	0	0	11	1	2
0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
1	2	2	1	4	6	9	4	5	6	2	1	1	1	7
0	0	1	0	0	0	0	0	1	0	0	1	1	0	0
0	0	0	5	0	0	0	0	0	0	0	0	0	0	0
5	3	2	31	4	11	13	14	3	9	1	2	10	1	7
0	0	3	0	1	0	0	0	3	0	0	0	1	0	0
0	0	2	1	0	1	4	1	0	0	3	1	1	1	3
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	1	0	0	1	2	0	0	0	0	0	0
0	0	0	0	0	2	3	2	0	0	0	1	2	2	0
8	8	6	9	4	0	1	6	11	21	0	3	8	5	1
342	450	358	289	432	388	315	403	367	353	389	407	373	414	399
1	0	0	0	0	0	1	1	0	0	0	0	0	0	0
0	0	8	2	0	0	1	0	0	1	0	0	1	0	0
1	3	0	1	1	1	2	2	1	2	1	1	1	0	1
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	3.5	0.5	0	1	1	1	2	0	0	4	0	1
0	0	1	2	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	2	0	0	0	2	0	0	0	0	0	0
3	0	2	1	0	0	1	1	1	1	0	0	1	0	0
0	0	0	0	1	0	0	0	2	0	0	0	0	0	0
3	2	0	1	0	0	5	2	0	0	2	1	2	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	1	0	0	5	1	2	1	0	0	0	0	0
0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
0	0.5	0	0	0.5	0	0	0	0.5	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
419	474.5	417	424.5	471	435	400	458	425.5	422	400	422	434	426	432

Table 3
Quantitative diatom abundance counts, *Hyalochaete Chaetoceros* spp. resting spore free

Species	Depth (mbsf)	18.898	18.903	18.894	20.23	18.77	20.39	19.58	17.9	17.88	19.72	19.2	20.47	19.215	18.875	20.157
	Number of FOV	44	83	61	57	101	153	92	44	57	41	116	39	52	59	108
	Mass (g)	0.0066	0.0053	0.005	0.0067	0.006	0.0066	0.006	0.0059	0.006	0.0069	0.0058	0.0056	0.0061	0.007	0.0055
	Lamina type	LT1	LT1	LT1	LT1	LT1	LT2	LT2	LT2	LT2	LT2	LT3	LT3	LT3	LT3	LT3
Actinocyclus actinochilus (Ehrenberg) Simonsen		0	4	0	1	0	3	1	1	0	2	1	1	1	0	1
Actinocyclus curvatulus Janisch in Schmidt		0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Asteromphalus spp. (Ehrenberg)		2	2	1	2	3	3	0	0	0	6	1	2	1	3	5
Azpeitia tabularis (Grunow) Fryxell and Sims		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cocconeis spp. Ehrenberg		0	0	0	0	0	0	0	0	0	0	1	0	0	0	2
Corethron pennatum (Grunow) Ostenfeld		0	0	5	3	1	127	122	186	158	134	2	8	3	1	11
Coscinodiscus spp. Ehrenberg		0	3	1	0	0	0	0	0	0	0	0	0	0	0	0
Cyclotella spp.(Kützing) Brébisson		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eucampia antarctica (Castracane) Mangin		0	5	2	3	1	3	8	2	2	7	6	4	10	11	9
Fragilariopsis curta (Van Heurck) Hustedt		123	136	113	122	173	93	97	101	93	103	62	104	85	68	69
Fragilariopsis cylindrus (Grunow) Krieger		0	42	12	12	39	16	68	58	102	31	11	125	73	46	69
Fragilariopsis cylindriformis (Hasle) Hasle		0	0	1	0	0	0	1	2	0	0	0	8	1	1	3
Fragilariopsis kerguelensis (O'Meara) Hustedt		51	43	30	42	60	25	25	19	4	15	71	12	14	21	55
Fragilariopsis obliquecostata (Van Heurck) Heiden		3	8	4	4	3	1	2	0	1	2	3	0	2	0	2
Fragilariopsis pseudonana (Hasle) Hasle		1	1	3	0	0	0	3	1	1	0	0	7	1	0	0
Fragilariopsis rhombica (O'Meara) Hustedt		58	41	61	61	43	51	23	16	8	55	103	67	49	135	56
Fragilariopsis ritscheri (Hustedt) Hasle		7	6	5	8	10	23	16	2	3	13	8	2	4	2	8
Fragilariopsis separanda Hustedt		88	33	75	2	17	7	2	2	13	0	0	17	4	5	18
Fragilariopsis sublinearis (Van Heurck) Heiden		0	3	0	1	0	1	2	0	0	2	2	0	0	1	0
Fragilariopsis vanheurckii (M. Pergallo) Hustedt		1	1	4	1	1	1	1	4	0	2	4	0	4	0	1
Fragilariopsis spp. Hustedt		13	19	6	3	2	3	1	4	8	6	4	5	0	1	11
Hyalochaete Chaetoceros spp. (vegetative) Gran		28	28	37	21	60	53	23	5	10	14	8	7	14	21	34
Navicula spp. Bory de St-Vincent		0	1	5	0	1	2	3	0	1	0	2	1	2	3	2
Odontella weissflogii (Janisch) Grunow		0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Phaeoceros Chaetoceros spp. Gran		39	6	10	3	4	0	3	5	12	11	39	5	6	10	10
Porosira glacialis (Grunow) Jørgensen		7	5	8	31	14	13	10	0	1	12	10	0	10	6	11
Porosira pseudodenticula (Hustedt) Jousé		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Proboscia inermis (Castracane) Jordan and Ligowski		0	5	1	0	1	1	2	0	5	1	6	8	14	17	1
Proboscia truncata (Karsten) Nöthig and Ligowski		0	1	0	0	0	0	0	0	0	2	3	1	1	5	0
Pseudo-nitzschia turgidula (Hustedt) Hasle		12.5	20	14	1.5	3	0.5	6.5	7.5	2	0	13	6	8	22.5	14
Rhizosolenia antennata f. *antennata* (Ehrenberg) Brown		0	0	0	0	0	0	1	0	0	0	6	0	1	0	1
Rhizosolenia antennata f. *semispina* Sundström		0	1	5	1	12	5	4	0	0	1	29	8	72	27	24
Rhizosolenia polydactyla Castracane f. *polydactyla*		0	0	0	0	1	0	0	0	0	0	0	1	2	0	0
Rhizosolenia simplex Karsten		2	1	8	0	0	0	0	0	0	1	6	6	23	3	3
Rhizosolenia spp. Brightwell		0	0	0	0	1	0	0	0	0	0	2	0	0	2	0
Stellarima microtrias (resting spore) (Ehrenberg) Hasle and Sims		0	0	0	2	1	1	0	0	0	2	1	0	0	0	0
Trachyneis aspera (Ehrenberg) Cleve		0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Thalassiosira antarctica (resting spore) Comber		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassiosira antarctica (vegetative) Comber		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassiosira gracilis v. *expecta* (Van Landingham) Fryxell and Hasle		2	3	1	5	2	3	0	0	0	3	0	1	2	4	2
Thalassiosira gracilis v. *gracilis* (Karsten) Hustedt		5	0	7	10	5	7	3	3	5	5	12	1	1	3	8
Thalassiosira gravida Cleve		3	3	1	4	3	0	0	0	0	0	3	0	1	14	3
Thalassiosira lentiginosa (Janisch) Fryxell		3	5	13	14	9	8	9	2	0	4	17	2	8	4	11
Thalassiosira lineata Jousé		0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Thalassiosira oestrupii (Ostenfeld) Hasle		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassiosira oliverana (O'Meara) Makarova and Nikolaev		0	1	0	1	0	0	0	0	0	1	0	0	0	0	1
Thalassiosira poroseriata (Ramsfjell) Hasle		2	2	2	54	0	2	5	1	0	2	7	0	1	6	1
Thalassiosira ritscheri (Hustedt) Hasle		0	0	0	7	1	0	0	0	0	1	1	0	2	0	3
Thalassiosira tumida (Janisch) Hasle		8	0	6	13	7	3	2	5	1	3	11	3	6	4	5
Thalassiosira scotia Fryxell and Hoban		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thalassiosira spp. Cleve		2	2	4	7	3	2	0	2	0	0	1	0	2	2	0
Thalassiothrix antarctica Schimper ex Karsten		1	0.5	1	0.5	1.5	1	0	0.5	0.5	0	0.5	0	0.5	3.5	0
Trichotoxon reinboldii (Van Heurck) Reid and Round		3	0.5	0	0.5	0.5	1	0.5	0	0	0	0.5	0	1.5	2	0.5
Unidentified centrics		0	2	1	0	0	2	1	0	0	0	0	0	2	0	0
Unidentified pennates		0.5	0	0	0	0	0	0	0	0	0	0	0	1	0	0
TOTAL:		467	434	447	440.5	484	462.5	445	429	430.5	442	457	412	434	455	455.5

FOV = Field of View. mbsf = metres below sea floor. LT = Lamina Type.

19.31	19.521	19.74	20.466	20.54	18.9	18.889	18.887	19.36	19.96	19.528	19.536	19.716	19.536	20.586
39	92	68	45	70	45	37	49	56	79	71	104	57	106	78
0.0051	0.0068	0.0051	0.0056	0.0059	0.008	0.0093	0.0093	0.0095	0.0081	0.0083	0.007	0.0097	0.0067	0.0085
LT4	LT4	LT4	LT4	LT4	LT5	LT5	LT5	LT5	LT5	LT6	LT6	LT6	LT6	LT6
0	0	0	2	1	0	3	0	4	0	2	5	4	1	1
0	0	0	0	1	0	1	1	0	0	0	0	0	0	0
0	2	3	2	4	3	0	3	0	7	3	3	2	1	2
0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
5	40	17	13	5	1	1	4	23	3	9	7	25	34	6
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
1	24	8	0	8	2	1	9	19	2	9	9	9	20	5
156	79	148	95	153	184	132	179	95	98	81	83	130	67	106
136	4	39	154	21	12	15	4	26	52	23	4	22	3	15
0	0	0	2	1	0	0	1	1	0	0	0	0	0	0
14	8	36	7	38	43	61	73	54	38	29	46	43	36	50
4	1	5	0	0	1	1	5	7	5	25	4	5	1	4
4	0	1	7	2	0	2	1	0	4	0	1	0	0	1
18	108	47	81	99	95	85	67	58	79	14	62	68	91	96
14	12	17	0	4	7	6	12	22	5	11	6	10	10	17
0	7	11	2	10	8	22	34	13	25	69	48	11	16	19
3	4	4	0	2	0	0	0	1	0	0	0	1	6	16
4	1	2	0	4	1	3	0	7	4	2	0	1	3	0
5	12	4	1	2	14	4	13	4	10	7	3	4	7	0
26	97	18	12	47	12	1	10	15	28	31	35	11	86	6
5	0	1	0	2	3	3	1	1	3	2	0	4	2	2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	4	20	13	13	1	6	7	2	1	4	4	2	6	4
2	57	16	1	2	6	8	10	11	13	66	56	38	50	25
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	2	2	2	5	0	0	2	1	1	2	1	0	0	2
1	1	0	0	2	1	0	1	0	0	0	0	0	0	0
4.5	3	11.5	8	12	5	2	2.5	4	13	2.5	3	7.5	5	10
1	0	0	1	1	0	0	0	0	0	0	0	1	2	1
1	6	4	13	3	0	5	4	1	6	0	1	4	7	4
0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
0	1	0	0	0	1	9	1	0	1	4	3	0	1	0
0	0	3	0	0	0	0	0	0	1	0	0	0	0	0
0	2	0	1	0	0	0	0	1	0	0	3	0	0	0
1	0	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0
0	0	0	0	0	0	3	2	2	0	0	0	0	0	0
0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
2	2	3	0	3	1	1	3	3	4	2	6	2	5	10
8	2	6	3	9	3	3	12	12	8	4	5	6	1	10
2	2	1	1	6	0	2	0	1	2	1	1	1	1	3
7	14	7	1	5	5	11	13	17	15	8	12	6	13	10
0	0	0	0	0	1	2	0	0	1	0	2	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3	5	0	3	4	2	3	8	3	1	4	2	6	0
0	7	2	2	0	0	0	0	1	2	1	2	3	9	1
8	5	6	5	7	1	8	3	6	3	9	15	4	8	11
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	1	3	0	2	3	3	3	2	6	0	4	1
0	0.5	0	0	2	0	0.5	0.5	1.5	0	0	0	0	0	0.5
0	1	0.5	0	0	0.5	0.5	1.5	0	0.5	0	0	0.5	0	0.5
1	0	0	1	0	0	1	0	0	0	3	0	0	0	0
0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
448.5	511.5	449	431	480	416.5	407	486	428.5	441.5	435	441	427	502	439

3. Results

Five lamina and one sub-lamina type were determined in the intervals studied. These lamina and sub-lamina types were classified according to the terrigenous / biogenic content and diatom assemblages. The diatom assemblages were used to interpret environmental conditions during lamina deposition. As *Hyalochaete Chaetoceros* spp. resting spores (CRS) overwhelmingly dominate the laminated sediment (78.8–93.8% of the assemblages, Table 4), the more minor constituents of the assemblage, which are visually dominant in the BSEI photographs, were used to categorise and name the lamina types.

3.1. Biogenic laminae

Biogenic laminae are composed of almost pure diatom ooze with very little terrigenous material and are present throughout the sampled interval. BSEI photographs of these laminae are dark due to the high porosity of the diatom ooze (Fig. 4A–D) and the low atomic number of the carbon-based resin which fills diatom frustules (the higher the atomic number of the specimen examined in BSEI, the more backscattered electrons are generated by elastic collisions between energetic beam electrons and atoms within the specimen; Goldstein et al., 1981; Pye and Krinsley, 1984). The four types of biogenic laminae present are detailed below.

3.1.1. Lamina Type 1

Lamina Type 1 occurred 62 times throughout the studied interval making up 15% of the total sediment thickness. The thickness of Type 1 laminae ranged from 0.4 to 46.9 mm ($n=62$ mean = 5.1 mm $\sigma=6.6$ mm). BSEI analysis of lamina Type 1 indicates that the diatom assemblage is overwhelmingly composed of *Hyalochaete Chaetoceros* spp. resting spores (CRS) (Fig. 4A), confirmed by CRS constituting 90.5% relative abundance of the total diatom assemblage (Table 4). The visually dominant minor constituents of the assemblage observed in BSEI photographs are *Fragilariopsis* spp., *Corethron pennatum* and *Rhizosolenia* spp., but the CRS free quantitative diatom assemblage counts (Table 4) are dominated by *Fragilariopsis* spp. (70.2%: the most dominant are *F. curta*, *F. rhombica*, *F. kerguelensis*, and *F. separanda*) and *Thalassiosira* spp. (9.7%) while *C. pennatum* and *Rhizosolenia* spp. only constitute 1.8% (Table 4). This lamina type is clearly characterised by very high abundance of CRS and we call these laminae "near-monogeneric *Hyalochaete Chaetoceros* spp. resting spore biogenic laminae".

3.1.2. Lamina Type 2

Type 2 laminae occurred 28 times throughout the studied interval and range in thickness from 2.1 to 81.0 mm ($n=28$ mean = 17.4 mm $\sigma=21.8$ mm). Half of the laminae have thicknesses over 10.0 mm, three of which are greater than 50.0 mm thick. Lamina Type 2 makes up 25% of the total sediment thickness of the studied interval. *C. pennatum* visually dominates the BSEI photographs (Fig. 4B) and constitutes 32.9% of the CRS free quantitative diatom assemblage count (Table 4). Other important constituents of the assemblage observed in BSEI photographs are CRS, *Fragilariopsis* spp. and *Rhizosolenia* spp. CRS constitute on average 78.8% relative abundance of the total diatom assemblage (Table 4). *F. curta* and *F. cylindrus* constitute 22.0% and 12.4% respectively of the CRS free quantitative diatom assemblage count and *Rhizosolenia* spp. 0.5% (Table 4). These laminae are typified by *C. pennatum* and CRS, but because of the visual dominance of *C. pennatum* in the BSEI analysis lamina Type 2 will be called "biogenic laminae characterised by *C. pennatum*".

3.1.3. Lamina Type 3

Lamina Type 3 occurs 8 times between 18.88 and 20.58 mbsf. These laminae range in thicknesses from 0.4 to 23.0 mm ($n=8$ mean = 4.2 mm $\sigma=2.6$ mm), making up 2% of the total sediment thickness of the intervals analysed. BSEI analysis of the lamina type shows that *Rhizosolenia* spp. visually dominate the diatom assemblage (Fig. 4C). *Rhizosolenia* spp. account for 9.8% in the CRS free quantitative diatom assemblage counts (Table 4), specifically 7.2% *R. antennata v. semispina* and 1.9% *R. simplex*. The other constituents of the assemblage identified as visually important in BSEI analyses are CRS, *Fragilariopsis* spp. and *C. pennatum*. CRS constitute on average 80.4% relative abundance of the total diatom assemblage (Table 4). In the CRS free quantitative diatom assemblage counts the most abundant species are *Fragilariopsis rhombica* (18.5%), *F. curta* (17.5%) and *F. cylindrus* (14.6%). *Proboscia inermis* spring form (2.1%), *P. truncata* spring and winter forms (0.5%) and *C. pennatum* (1.1%) are also present in the CRS free diatom assemblage. These laminae are typified by *Rhizosolenia* spp. and CRS. As *Rhizosolenia* spp. are visually dominant in the BSEI analysis this lamina type will be called "biogenic laminae characterised by *Rhizosolenia* spp.".

Table 4
Relative abundance of diatoms, all species; relative abundance of diatoms, *Hyalochaete Chaetoceros* spp. resting spore free; and absolute abundance of diatom species (valves/g of dry sediment × 10^6)

Species	Lamina Type 1	Lamina Type 2	Lamina Type 3	Lamina Type 4	Lamina Type 5	Sub-lamina Type 6
Relative abundance of diatoms, all species						
Hyalochaete Chaetoceros spp. (resting spore) Gran	90.5	78.8	80.4	84.8	85.3	93.8
Corethron pennatum (Grunow) Ostenfeld	0.0	6.9	0.3	0.4	0.2	0.1
Fragilariopsis spp. Hustedt	5.8	10.1	12.7	10.8	10.2	4.4
Porosira glacialis (Grunow) Jørgensen	0.2	0.1	0.2	0.3	0.4	0.2
Rhizosolenia spp. Brightwell	0.2	0.2	2.0	0.2	0.1	0.0
Thalassiosira spp. Cleve	0.7	0.6	1.1	1.0	1.2	0.3
All other species	2.6	3.3	3.3	2.5	2.6	1.2
Total:	100.0	100.0	100.0	100.0	100.0	100.0
Relative abundance of diatoms, Hyalochaete Chaetoceros spp. resting spore free						
Corethron pennatum (Grunow) Ostenfeld	0.4	32.9	1.1	3.4	1.5	3.6
Fragilariopsis spp. Hustedt	70.2	51.3	64.3	68.7	77.7	61.4
Hyalochaete Chaetoceros spp. vegetative Gran	7.7	4.8	3.8	8.6	3.0	7.5
Phaeoceros Chaetoceros spp. Gran	2.7	1.4	3.2	2.7	0.8	0.9
Porosira glacialis (Grunow) Jørgensen	2.9	1.6	1.7	3.4	2.2	10.5
Rhizosolenia spp. Brightwell	1.4	0.5	9.8	1.5	1.4	1.2
Thalassiosira spp. Cleve	9.7	3.7	7.0	6.2	8.5	8.9
All other species	5.0	3.8	9.1	5.5	4.9	6.0
Total:	100.0	100.0	100.0	100.0	100.0	100.0
Absolute abundance of diatoms						
Hyalochaete Chaetoceros spp. (resting spore) Gran	4198.5	1238.0	1642.7	2639.7	1659.1	3629.8
Corethron pennatum (Grunow) Ostenfeld	2.5	98.4	3.3	11.3	3.3	3.4
Fragilariopsis spp. Hustedt	192.7	146.2	179.0	231.9	201.6	103.8
Porosira glacialis (Grunow) Jørgensen	10.4	1.3	2.5	9.9	6.9	5.7
Rhizosolenia spp. Brightwell	8.7	3.1	23.1	3.1	1.4	0.0
Thalassiosira spp. Cleve	17.1	6.3	15.2	27.0	21.0	8.3
All other species	75.3	44.2	49.5	69.3	39.8	41.3
Total:	4505.2	1537.5	1915.3	2992.2	1933.1	3792.3

Thalassiosira spp. = all *Thalassiosira* species. *Rhizosolenia* spp. = all *Rhizosolenia* species. *Fragilariopsis* spp. = all *Fragilariopsis* species.

3.1.4. Lamina Type 4

Forty-five laminae of this type occur in the studied interval and make up 18% of the total sediment thickness. These laminae range in thicknesses from 0.5 to 38.0 mm ($n=45$ mean = 8.5 mm $\sigma=8.7$ mm). BSEI analyses show that the diatom assemblage of this lamina type is composed mainly of CRS (Fig. 4D) and other visually dominant species are *C. pennatum*, *Fragilariopsis* spp., *Rhizosolenia* spp. BSEI analyses of this lamina type indicate that the diatom assemblage is not always homogeneous. In particular areas of BSEI photographs are visually dominated by *C. pennatum* and to a lesser degree, *Rhizosolenia* spp. CRS constitute on average 84.8% relative abundance of the total diatom assemblage (Table 4). CRS free quantitative diatom assemblage counts are dominated by *Fragilariopsis* spp. (68.7%; the most dominant are *F. curta*, *F. cylindrus* and *F. rhombica*), *C. pennatum* (3.4%) and *Porosira glacialis* resting spores (3.4%) (Table 4). When compared to the near-monogeneric CRS laminae, this lamina type has, in total, lower absolute abundance of CRS and *Rhizosolenia* spp., similar abundances of *Fragilariopsis* spp. and *P. glacialis* resting spores, but more abundant *C. pennatum* and *Thalassiosira* spp. (Table 4). These laminae are characterised by CRS and several other species, therefore we call this lamina type “mixed diatom assemblage biogenic laminae”.

3.2. Terrigenous laminae

Terrigenous laminae are identified by a higher proportion of terrigenous grains relative to the biogenic laminae. There is variation in size (ice-rafted silt, clay and sand) and amount of terrigenous grains in the terrigenous laminae in the studied section. The BSEI photographs (Fig. 4E–F) of these laminae are light in colour due to the high average atomic number of the terrigenous grains.

3.2.1. Lamina Type 5

Lamina Type 5 occurs 112 times throughout the investigated interval. These laminae range in thicknesses from 0.4 to 64.3 mm ($n=112$ mean$=7.3$ mm $\sigma=8.3$ mm) and make up 39% of the total sediment thickness of the analysed intervals. BSEI analyses of this lamina type indicates that the diatom assemblage is near-monogeneric CRS (Fig. 4E) (CRS constitute on average 85.3% relative abundance of total diatom assemblage; Table 4), however, a visually more diverse minor diatom assemblage (including: *C. pennatum*, *Coscinodiscus bouvet*, *Fragilariopsis* spp., *P. glacialis* resting spores, *Stellarima microtrias* resting spores, and to an even more minor extent *Eucampia antarctica*, *Rhizosolenia* spp., *Trigonium arcticum*) is present in comparison to the biogenic mixed diatom assemblage laminae (discussed in Section 3.1.4). The CRS free quantitative diatom assemblage counts show that the diverse minor diatom assemblage is dominated by *Fragilariopsis* spp. (77.7%: the most dominant are *F. curta*, *F. kerguelensis* and *F. rhombica*) and *Thalassiosira* spp. (8.5%). *C. pennatum* and *Rhizosolenia* spp. have relative abundances of 1.5% and 1.4%, respectively (Table 4). These laminae are characterised by CRS and a diverse minor diatom assemblage, and are called “mixed diatom assemblage terrigenous laminae”.

3.2.2. Sub-lamina Type 6

Twenty-three sub-laminae of this type are present in the studied interval and range in thickness from 0.5 to 5.5 mm ($n=23$ mean$=1.4$ mm $\sigma=1.1$ mm). This sub-lamina type makes up 2% of the total sediment thickness sampled and become less common above 17.79 mbsf. BSEI analyses reveal this sub-lamina type visually is characterised by *P. glacialis* resting spores (RS) (often observed within vegetative remains) (Fig. 4F) (*P. glacialis* RS constitute on average 10.5% of the CRS free quantitative diatom assemblage counts; Table 4). These sub-laminae are found within, and mostly at the top of, lamina Type 5, the mixed diatom assemblage terrigenous laminae. On nine occasions *P. glacialis* RS are noted to dominate the assemblage of thin terrigenous laminae (1.0–2.0 mm thick). CRS constitute on average 93.8% relative abundance of the total diatom assemblage (Table 4). In the CRS free quantitative diatom assemblage counts the most abundant species are *F. curta* (20.8%) and *F. rhombica* (14.8%) however, this sub-lamina type is visually characterised by *P. glacialis* RS and is called “terrigenous sub-lamina characterised by *P. glacialis* RS”.

3.3. Description of lamina relationships

Two hundred and fifty-five laminae and twenty-three sub-laminae are present in the laminated intervals investigated. Out of all the lamina and sub-lamina types, the near-monogeneric CRS laminae have the greatest absolute abundance of diatoms, 4505×10^6 valves per gram of dry sediment (Table 4). The terrigenous sub-laminae characterised by *P. glacialis* resting spores have the second highest abundance, 3792×10^6 valves per gram of dry sediment. Laminae characterised by *C. pennatum* and *Rhizosolenia* spp. and the mixed diatom assemblage terrigenous laminae have the lowest abundance of diatoms, ranging from 1538–1933×10^6 valves per gram of dry sediment (Table 4).

Variable combinations of the different types of lamina have been observed (Fig. 3), however, a typical succession of the lamina types can be defined: near-monogeneric *Hyalochaete Chaetoceros* spp. resting spore (CRS) laminae (Type 1), are followed by laminae characterised by *C. pennatum* (Type 2), laminae characterised by *Rhizosolenia* spp. (Type 3), mixed diatom assemblage laminae (Type 4), mixed diatom assemblage terrigenous laminae (Type 5), and finally terrigenous sub-laminae characterised by *P. glacialis* RS (Type 6) (Fig. 5). This typical sequence, ranging from

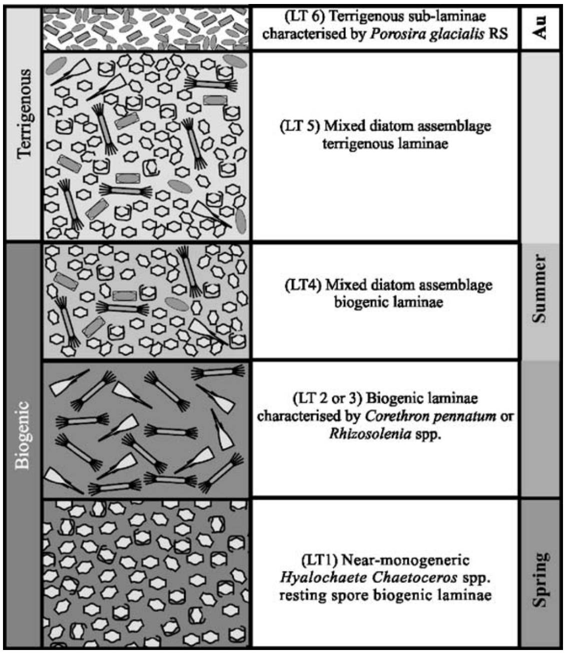


Fig. 5. Schematic representation of the biogenic and terrigenous laminae and terrigenous sub-laminae. Compiled from BSEI data. LT=Lamina Type. Au=Autumn. RS=Resting Spores.

complete to only a few components present, is repeated up through the studied section (Fig. 3).

4. Discussion

Sediment trap studies have been conducted circum Antarctica e.g. Antarctic Peninsula, Weddell Sea (Leventer, 1991; Abelmann and Gersonde, 1991), providing records of diatom productivity events throughout the austral growing season (October to April). The correlation of this temporal diatom assemblage information with environmental and/or water mass conditions provides an insights into the ecological preferences of diatom species. No sediment trap data exists for the George V Coast region so we have referred to sediment trap data from other Antarctic sites to aid our interpretations.

The six lamina/sub-lamina types identified will be discussed individually. Interpretation of the diatom assemblages provides evidence for the environmental conditions (such as sea ice cover, nutrient levels and water column stability) which prevailed during, or immediately prior to, sediment lamina deposition. The overwhelming dominance of *Hyalochaete Chaetoceros* spp. in all of the lamina types indicates that water column conditions were suitable for this sub-genus throughout the growing season. Nutrient levels must have been high and water column stratification sufficiently strong between October and March to produce this sustained high productivity that dominates the diatom assemblage. Modern sediments from the Mertz Ninnis Trough have much lower relative abundances of *Hyalochaete Chaetoceros* spp. resting spores (19.8–25.4%; Leventer, 1992) than the post-glacial sediments (78.8–93.8%; Table 4) examined in this study indicating that modern water column conditions in the region are not as suitable for *Hyalochaete Chaetoceros* spp. as they were in post-glacial times. Absolute diatom abundance of modern sediments from the Mertz Ninnis Trough are also much lower ($\sim 200 \times 10^6$ valves per gram of dry sediment; Leventer, 1992) than in post-glacial sediments (~1500–4500 valves per gram of dry sediment; Table 4), suggesting that environmental conditions were more suitable for high primary productivity in post-glacial times.

4.1. Lamina Type 1: near-monogeneric Hyalochaete Chaetoceros spp. resting spore (CRS) biogenic laminae

The sub-genus *Hyalochaete Chaetoceros* is common in pack ice (Garrison et al., 1987; Garrison and Buck, 1985, 1989; Gleitz et al., 1998) and favours proximity to sea ice (Leventer, 1991; Crosta et al., 1997). Modern sediment trap data from the Antarctic Peninsula suggests that *Hyalochaete Chaetoceros* spp. blooms are associated with the melting of sea ice in the austral spring and water column stratification (Leventer, 1991; Crosta et al., 1997). Resting spores are a survival strategy response to environmental stress and high concentrations of CRS in the sediments are interpreted as being indicative of very high primary productivity in surface waters (Donegan and Schrader, 1982). *F. curta* is a species common in pack and fast ice (Garrison et al., 1983; Gersonde, 1984; Krebs et al., 1987; Garrison and Buck, 1989) and is also found in high abundance in the water column adjacent to the ice edge (Garrison et al., 1983; Leventer and Dunbar, 1996). *F. rhombica* has also been observed in sea ice samples (Gersonde, 1984; Krebs et al., 1987; Garrison and Buck, 1989). The high abundance of CRS in this lamina type indicates that primary productivity was high, a result of nutrient-rich well-stratified water column (Leventer et al., 1993, 1996). Deposition of this lamina type is interpreted to have occurred in early spring when increased solar insolation caused sea ice melt, an interpretation supported by relatively high abundance of *F. curta* and *F. rhombica*. We interpret the near-monogeneric CRS biogenic laminae to be a result of earliest spring productivity (Fig. 5).

4.2. Lamina Type 2 and 3: biogenic laminae characterised by Corethron pennatum or Rhizosolenia spp.

The diatom assemblages of these two biogenic laminae are characterised by different genera. Since *C. pennatum* and *Rhizosolenia* spp. are associated with similar water column conditions and are closely related (molecular data; Medlin et al., 1994) these two lamina types will be discussed together for the rest of the paper.

C. pennatum, which characterises lamina Type 2, usually reaches its highest concentrations along the Antarctic coast and can dominate the phytoplankton (Sommer, 1991; Ligowski et al., 1992). *C. pennatum* occurs in open water with little sea ice (Fryxell and Hasle, 1971; Makarov, 1984; Leventer and Dunbar, 1987). Crawford (1995) observed a large diatom bloom overwhelmingly dominated by *C. pennatum* in the South Atlantic in late November. The species has positive buoyancy (Crawford, 1995) which suggests that it may be able to exploit a well-stratified water column, migrating down to take advantage of higher nutrient content at depth and up for higher light levels for photosynthesis (Leventer et al., 2002) to maximise bloom conditions. Deterioration in the water column stability during the summer to autumn transition could potentially trigger a mass sinking of the bloom (Kemp et al., 2000). Relatively high numbers of *F. curta* and *F. cylindrus* occur in this lamina type. Both of these species occur in coastal areas influenced by sea ice (Truesdale and Kellogg, 1979; Leventer and Dunbar, 1988; Leventer, 1992, 1998; Zielinski and Gersonde, 1997). *F. curta* is associated with pack, fast and melting sea ice and surface water stratification (Leventer and Dunbar, 1987; Cunningham and Leventer, 1998; Leventer, 1998). *F. curta* is also noted in very high abundances in the water column near the sea ice edge (Fryxell, 1989; Tanimura et al., 1990; Kang and Fryxell, 1992, 1993; Leventer and Dunbar, 1996). *Fragilariopsis cylindrus* has been observed in open waters (Kang and Fryxell, 1992; Moisan and Fryxell, 1993) and in ice-covered areas (Garrison et al., 1983; Garrison and Buck, 1985; Garrison et al., 1987; Moisan and Fryxell, 1993). In open waters *F. cylindrus* occurs in areas affected by sea ice melt (e.g. Stockwell et al., 1991) or is found in waters after ice-break out (McMinn and Hodgson, 1993). Von Quillfeldt (2004) suggests that *F. cylindrus* is an indicator species for cold water rather than sea ice.

Therefore, the deposition of the biogenic lamina type characterised by *C. pennatum* is interpreted to be a result of open water productivity in front of a relatively stable sea ice edge. The position of this lamina type in the typical sequence of lamina types (following lamina Type 1, earliest spring deposition) and the water column conditions suggest that this lamina type was deposited in late spring/early summer (Fig. 5).

Rhizosolenia spp. characterise lamina Type 3 and are a common component of the Antarctic phytoplankton. This genus is minor, but important, as a contributor to sea floor sediments (Armand and Zielinski, 2001). *Rhizosolenia* spp. can form large blooms or mats in open water (Harbison et al., 1977; Alldredge and Silver, 1982; Kemp et al., 1999) and have been reported in high abundances from Antarctic waters (Hart, 1934; Holm-Hansen et al., 1989; Leventer et al., 1996). Froneman et al. (1995) and Kang et al. (2001) have observed *R. antennata* f. *semispina* to be abundant in open waters of late summer. *Rhizosolenia simplex* has been observed south of the Antarctic Divergence (Semina, 1979) and in the open ocean of the Bellinghausen and Weddell Seas (Ligowski, 1993). From the Antarctic Peninsula, late Holocene laminae rich in *Rhizosolenia* spp. are thought to have formed by rapid settling following a bloom (Leventer et al., 1996). Leventer et al. (2002) have suggested blooms of *Rhizosolenia* spp. and *Proboscia* spp. are present in summer beneath the thermocline during strong surface water stratification and that mass sedimentation of these species occurs in the autumn as strong mixing of the water column weakens the thermocline. Villareal et al. (1993; 1996) have shown that in the North Pacific *Rhizosolenia* spp. migrate up and down in the water column to increased depths to acquire nutrients and return to the nutrient poor surface waters to photosynthesise. The most abundant *Fragilariopsis* spp. in this lamina type is *F. rhombica.* Similar high relative abundances of this species have also been observed in surface sediment samples from this region (Leventer, 1992). The occurrence of *F. curta* and *F. cylindrus* in lamina Type 3 (as in lamina Type 2) suggests that at the time of lamina deposition open waters were influenced by sea ice. *P. inermis* occurs in this lamina type but little is known about its ecological preferences and distribution. However, Stickley et al. (2005) suggested that *P. inermis* is associated with open water conditions and interpreted the co-occurrence of *P. inermis* and *Rhizosolenia antennata* f. *semispina* in Mac.Robertson shelf deglacial laminated sediments to be an indication of increasingly oligotrophic warmer waters.

The deposition of the biogenic lamina type characterised by *Rhizosolenia* spp. is interpreted to be a consequence of oligotrophic open water conditions prevailing in front of a relatively stable sea ice edge. The environmental interpretation and position of this lamina type, characterised by *Rhizosolenia* spp., in the typical lamina succession is the same as lamina Type 2. This indicates that lamina Type 3 was also deposited in late spring/early summer (Fig. 5).

4.3. Lamina Type 4: mixed diatom assemblage biogenic laminae

The more mixed diatom assemblage within these laminae (less *Hyalochaete Chaetoceros* spp. and more *C. pennatum*, *Thalassiosira* spp. and *P. glacialis*) suggests a less well-stratified, more mixed surface water column. Bodungen (1986) describes waters in the northern Bransfield Strait that contain a diatom assemblage composed of *Chaetoceros* spp., *C. pennatum*, *Thalassiosira antarctica* and *Porosira* spp. in late December. The presence of *C. pennatum* and, to a lesser degree, *Rhizosolenia* spp. patches within the laminae suggest either that zooplankton grazing and resultant faecal pellets concentrated these species in the sediment or open water conditions with reduced water column mixing lasted for relatively short periods of time without concomitant laminae of Type 2/3 forming. Deeper mixing and the resultant destabilisation of the water column would cause mass sedimentation of the colonial diatoms (Kemp et al., 2000) and allow a more mixed assemblage to thrive. The occurrence of this lamina type after lamina Type 1, 2 or 3 in the typical sequence of laminae and mixed nature of the diatom assemblage suggests that deposition of lamina Type 4 occurred in the summer (Fig. 5).

4.4. Lamina Type 5: mixed diatom assemblage terrigenous laminae

The terrigenous component of these mixed diatom assemblage laminae represents the input of ice rafted material from the Mertz Glacier Tongue (Domack and Anderson, 1983) and/or Modified Circumpolar Deep Water (MCDW) entrained fine grained sediments from the surrounding shelf area (Dunbar et al., 1985; Domack, 1988; Rintoul, 1998; Bindoff et al., 2001). *C. pennatum* and *R. antennata* f. *semispina* (the most dominant *Rhizosolenia* spp. present in this lamina type; Table 3) are considered to be indicative of open water conditions (Fryxell and Hasle, 1971; Makarov, 1984; Leventer and Dunbar, 1987; Ligowski, 1993). *C. pennatum* has been reported as a component of the ice edge phytoplankton (Marra and Boardman, 1984) and *R. antennata* f. *semispina* and *R. simplex* have been observed in open ocean conditions (Ligowski, 1993). *P. glacialis* is associated with waters adjacent to the coast or sea-ice (Hasle, 1973), in particular, slush and wave exposed shore ice (Krebs et al., 1987), but does not live within sea ice (Horner, 1985; Watanabe, 1988; Garrison, 1991; Scott et al., 1994). *C. bouvet* is a neritic species (Priddle and Thomas, 1989) and *S. microtrias* is associated with shelf ice and the surrounding shelf waters (Hasle et al., 1988). In summer, *S. microtrias* has been noted in very high abundance in fast sea-ice samples (Watanabe, 1982; Krebs et al., 1987; Tanimura et al., 1990) and during autumn, the resting spore is found in high abundances under sea-ice and is not present in the open ocean (Fryxell, 1989). *T. arcticum* lives epiphytically on algae (possibly saprophytic) at a depth of 200–300 m in the water column (Hendey, 1937; Tomas, 1966). Therefore, it is likely that this species was swept into the Mertz Ninnis Trough from the broad, relatively shallow Adélie and Mertz Banks and/or from Commonwealth Bay by High Salinity Shelf Water (Fig. 1).

The terrigenous component and the diatom assemblage suggests that this lamina type was deposited in summer/autumn (Fig. 5) when open water conditions were impinged upon by the growth of sea ice and there was an increase in bottom water currents (a result of increased sea ice growth; Rintoul, 1998; Bindoff et al., 2001).

4.5. Sub-lamina Type 6: terrigenous sub-laminae characterised by Porosira glacialis resting spores

As described in Section 4.4, *P. glacialis* has been observed in the water column adjacent to sea ice (Krebs et al., 1987). The *P. glacialis* resting spore sub-laminae is repeatedly observed to occur after lamina Type 5 in the typical lamina succession. The relatively thin sub-laminae suggest that there was a short, relatively intensive period of *P. glacialis* resting spore formation. *P. glacialis* resting spores and *T. antarctica* resting spores have been observed together in laminated sediments from the Mac.Robertson shelf (Stickley et al., 2005). This co-occurrence led to the suggestion that *P. glacialis* and *T. antarctica* share similar growth requirements (Stickley et al., 2005). *T. antarctica* is associated with low temperatures, low salinities and sea-ice (e.g. Hasle and Heimdal, 1968; Villareal and Fryxell, 1983). *T. antarctica* resting spores form as a result of environmental stress induced by sea ice formation (Maddison et al., 2005). Surface sediment data from the Ross Sea indicates that *T. antarctica* is associated with autumnal bloom events (Cunningham and Leventer, 1998). The information on the environmental preferences and seasonal bloom events of *T. antarctica* together with its co-occurrence with *P. glacialis,* combined with the position of the sub-lamina type in the typical lamina succession (Fig. 5), suggests that the *P. glacialis* resting spore sub-laminae were deposited in autumn when sea ice formation creates high salinity surface waters.

4.6. Lamina relationships

The difference in absolute diatom abundance between the different types of laminae results from changes in the water column stability, depth of mixing and surface water nutrient levels (e.g. micronutrient iron). As the sea ice melts at its maximum rates in the spring, stratification of the water column traps nutrients derived from the sea ice itself, MCDW (water mass reaches surface waters in winter) and aerosols [mineral aerosol concentrations reach a maximum in late spring and early summer (Tuncel et al., 1989; Wagenbach, 1996)]. The rapidly melting sea ice, elevated nutrient levels and stratified waters in spring would have been conducive to high primary productivity of *Hyalochaete Chaetoceros* spp. and the subsequent formation of near-monogeneric CRS biogenic laminae. The rapid growth of *Hyalochaete Chaetoceros* spp. blooms (in regions external to Antarctica; Grimm et al., 1996, 1997; Alldredge and Gotschalk, 1989) would deplete the nutrients in the water column. Lower nutrient concentration along with stable open water conditions in front of the sea ice edge would facilitate blooms of *C. pennatum* and *Rhizosolenia* spp. and subsequent deposition of biogenic laminae characterised by these diatoms. Surface water column mixing and deepening of the thermocline elevates surface water nutrient levels increasing productivity of a more mixed assemblage and deposition of mixed diatom assemblage biogenic laminae. Further bio-depletion of these nutrients would induce a decrease in productivity and the input of terrigenous material leads to deposition of mixed diatom assemblage terrigenous laminae. In autumn, the cooling of surface waters enables upwelling of nutrient-rich MCDW to re-supply surface waters, replenishing the waters depleted by phytoplankton growth. The proximity of sea ice and increased nutrients promote high productivity of *P. glacialis*, resulting in the formation of the terrigenous sub-laminae characterised by *P. glacialis* resting spores at the end of the growing season. A sharp transition from summer/autumn terrigenous laminae to spring/summer biogenic laminae suggests that there was little or no deposition in the winter. One hundred and sixteen annual cycles were identified in the studied interval.

Although the different types of laminae always occur in same sequence relative to each other in the laminated interval (Fig. 5), not every annual sedimentary increment contains all of the six types of laminae (Fig. 3). We suggest that this is the result of annual variability in the dynamics of the Mertz Glacier Polynya.

4.7. Polynya model for Mertz Ninnis Trough laminated sediments

The East Antarctic Ice Sheet grounding line reached the edge of the continental shelf at the last glacial maximum (Domack, 1982; Barnes, 1987; Eittreim et al., 1995) and the transition from subglacial to glacial-marine sedimentation occurred prior to ~ 9000 yr BP (Domack et al., 1991). Open water conditions and sea ice would therefore have prevailed in the region following ice sheet retreat, during which time the laminated sediments investigated here were deposited. Today the Mertz Glacier Polynya is situated above JPC10 core site and is considered likely to play a part in the intensity and distribution of plankton growth (Sambrotto et al., 2003). We believe post-glacial polynya dynamics enhance already high diatom productivity at this time circum Antarctica (Leventer et al., 2002; Maddison et al., 2005; Stickley et al., 2005).

4.7.1. Spring

In the spring solar radiation levels start to rise, melting the polynya sea ice margins and increasing open water area. A change in heat regime from latent heat to a sensible heat polynya occurs. Nutrient-rich MCDW is prevented from reaching surface waters by sea ice-melt-induced water column stratification. However, a finite amount of nutrients, already supplied to surface waters during winter upwelling of MCDW, is trapped by the stratification. The reduced sea ice cover would allow elevated phytoplankton production to occur early in the growing season, just after the spring equinox (Sambrotto et al., 2003). These stratified, nutrient-rich waters allow *Hyalochaete Chaetoceros* spp. blooms to occur. Katabatic winds in Adélie Land have been shown to be intense and frequent through the growing season (Périard and Pettré, 1993) which can cause intermittent mixing of the stratified surface waters. Environmental stress created by this disruption would cause resting spore formation and the resultant deposition of near-monogeneric CRS biogenic laminae (Figs. 4A and 6a).

4.7.2. Summer

The continued high solar radiation in the region provides a continuous flux of heat further melting the sensible heat polynya margins. The sea ice edge at the shelf break also melts. Two scenarios can occur, which control the type of laminae deposited:

1. The embayment in the sea ice edge encroaches far enough to join the polynya by October. This has been observed to occur in 16% of winter months between 1987 and 1994 (Massom et al., 1998).
2. The sea ice edge embayment retreats later in the season, joining the polynya by November and the coast by December. This has been observed to be an annual occurrence (Massom et al., 2003).

Both of these scenarios produce open water conditions with little sea ice influence. Minimal water column mixing occurs due to low katabatic winds throughout the summer (Périard and Pettré, 1993). The open water conditions, created by October in scenario one, would allow open water adapted species such as *C. pennatum* and *Rhizosolenia* spp. to become established early in the season. The ability of these particular species to take advantage of nutrients trapped lower in the water column would allow large prolonged blooms to occur, deposition of which would result in thick biogenic

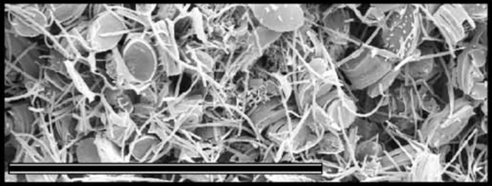
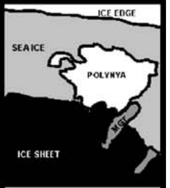
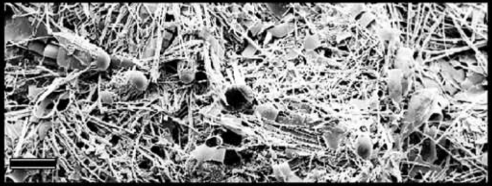
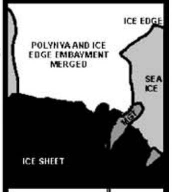
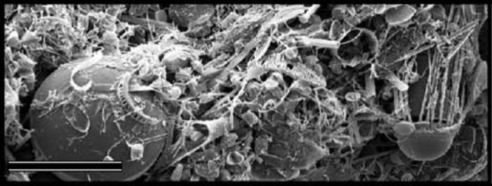
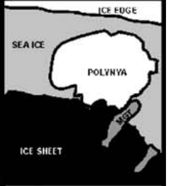
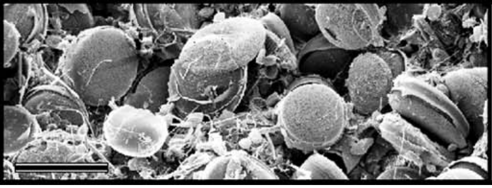
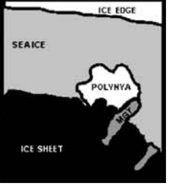
SEASON	LAMINA TYPE	LAMINA SPECIES ASSEMBLAGE	SEI MICROGRAPH OF LAMINA	POLYNYA HEAT STATUS	WATER CONDITIONS	POLYNYA AREAL EXTENT
a SPRING	BIOGENIC LAMINA TYPE 1	NEAR-MONOGENERIC *HYALOCHAETE CHAETOCEROS* SPP. RESTING SPORE		LATENT ↓ SENSIBLE HEAT POLYNYA	SEA ICE MELT AROUND THE MARGINS OF THE POLYNYA. **STRATIFIED** WATER COLUMN.	
b SPRING / SUMMER	BIOGENIC LAMINA TYPE 2	CHARACTERISED BY *CORETHRON PENNATUM*		SENSIBLE HEAT POLYNYA	ICE EDGE MARGIN MELTS FORMING AN EMBAYMENT WHICH MERGES WITH POLYNYA BY OCTOBER	
c SPRING / SUMMER	BIOGENIC LAMINA TYPE 3	CHARACTERISED BY *RHIZOSOLENIA* SPP.				
d SUMMER	BIOGENIC LAMINA TYPE 4	MIXED DIATOM ASSEMBLAGE (SEE TEXT).		SENSIBLE HEAT POLYNYA	ICE EDGE MARGIN MELTS FORMING AN EMBAYMENT WHICH MERGES WITH POLYNYA BY NOVEMBER	
e SUMMER	TERRIGENOUS LAMINA TYPE 5	MIXED DIATOM ASSEMBLAGE (SEE TEXT).		SENSIBLE HEAT POLYNYA	REDUCED SEA ICE MELT AND INCREASED WATER DENSITY. **MIXED** WATER COLUMN. ENTRAINED FINE GRAINED SEDIMENT TERRIGENOUS SOURCE	
f SUMMER / AUTUMN	TERRIGENOUS SUB-LAMINA TYPE 6	CHARACTERISED BY *POROSIRA GLACIALIS* RESTING SPORES		SENSIBLE ↓ LATENT HEAT POLYNYA	SEA ICE FORMS AND POLYNYA REDUCES IN SIZE. **HOMOGENEOUS** WATER COLUMN. ENTRAINED FINE GRAINED SEDIMENT TERRIGENOUS SOURCE	

Fig. 6. Summary table displaying polynya model and seasonal information responsible for the formation of multiple types of laminae through the deglaciation. Scale bars = 50 μm. MGT = Mertz Glacier Tongue.

laminae characterised by *C. pennatum* or *Rhizosolenia* spp. (Figs. 4B, C, 6b and c).

A greater number of mixed diatom assemblage laminae than laminae characterised by *C. pennatum* or *Rhizosolenia* spp. indicates that open water conditions created later in the season is the more common scenario. The reduced time with open water conditions means that *C. pennatum* and *Rhizosolenia* spp. are unable to establish such large biomass, as in scenario 1, therefore other diatom species are relatively more abundant. This results in a mixed diatom biogenic laminae being deposited, occasionally with patches characterised by *C. pennatum* and *Rhizosolenia* spp. (Figs. 4D and 6d).

4.7.3. Summer/autumn

A reduction in sea ice melting around the polynya margin creates denser surface waters and a deeper mixed surface layer, allowing upwelling MCDW to reach surface waters. Water column stratification is weaker, creating conditions suitable for a mixed diatom assemblage. MCDW and/or Antarctic Coastal Current transport open ocean diatoms into the region. The upwelling of MCDW onto the continental shelf entrains fine grained terrigenous sediments, which are transported landwards and deposited in the Mertz Ninnis Trough. Ice rafted material derived from the Mertz Glacier Tongue is also deposited in the trough. These terrigenous inputs into the laminae dilute the biogenic component (Figs. 4E and 6e) forming the mixed diatom assemblage terrigenous laminae.

4.7.4. Autumn

Solar radiation levels decrease which results in a return to latent heat conditions, where heat loss to the atmosphere is balanced by the latent heat of fusion of ice that continuously forms (Mysak and Huang, 1992). The reduction of polynya areal extent results in increased proximity of sea ice and marginally elevated seawater salinities, coincidental with the strongest annual average winds (Périard and Pettré, 1993) which in combination, would create conditions ideal for the growth and subsequent deposition of the terrigenous sub-laminae characterised by *P. glacialis* resting spores (Figs. 4F and 6f).

4.7.5. Winter

As ice production increases during the colder winter months the latent heat polynya decreases in size. Light levels are too low for diatom productivity in the winter months; therefore biogenic input to the sediment dramatically decreases, resulting in a hiatus between autumn and spring. MCDW is unrestricted by stratification and is able to reach surface waters, replenishing them with nutrients for the following growing season.

5. Conclusion

Diatom species blooms and the resultant deposition of diatom-rich post-glacial laminae and sub-laminae in the Mertz Ninnis Trough, East Antarctica, are seasonally controlled (light levels, sea ice extent and nutrient levels). We believe fluctuations in the size and heat regime of the Mertz Glacier Polynya (caused by variations in upwelling; katabatic wind strength and direction; areal extent and orientation of the Mertz Glacier Tongue) also play a role in controlling the type of laminae deposited. Four biogenic diatom ooze laminae types, one diatom-bearing terrigenous laminae type and one diatom-bearing terrigenous sub-laminae type have been identified in the laminated sequence. The biogenic laminae are deposited in spring and summer, and terrigenous laminae and sub-laminae in summer and autumn. The different laminae types consistently occur in the same order throughout the laminated interval. We believe this high-resolution record, demonstrates that the Mertz Glacier Polynya was active in early post-glacial times. Although primary productivity levels were higher in the post-glacial than today it would be valuable to collect water samples throughout the growing season in this region and to set up sediment traps to test the seasonal interpretations of the different lamina types presented here.

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