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Deglacial seasonal and sub-seasonal diatom record from Palmer Deep, Antarctica

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ABSTRACT: The Antarctic Peninsula is one of the most sensitive regions of Antarctica to climate change. Here, ecological and cryospheric systems respond rapidly to climate fluctuations. A 4.4 m thick laminated diatom ooze deposited during the last deglaciation is examined from a marine sediment core (ODP Site 1098) recovered from Basin I, Palmer Deep, western Antarctic Peninsula. This deglacial laminated interval was deposited directly over a glaciomarine diamict, hence during a globally recognised period of rapid climate change. The ultra-high-resolution deglacial record is analysed using SEM backscattered electron imagery and secondary electron imagery. Laminated to thinly bedded orange-brown diatom ooze (near monogeneric *Hyalochaete Chaetoceros* spp. resting spores) alternates with blue-grey terrigenous sediments (open water diatom species). These discrete laminae are interpreted as austral spring and summer signals respectively, with negligible winter deposition. Sub-seasonal sub-laminae are observed repeatedly through the summer laminae, suggesting variations in shelf waters throughout the summer. Tidal cycles, high storm intensities and/or intrusion of Circumpolar Deep Water onto the continental shelf introduced conditions which enhanced specific species productivity through the season. Copyright © 2005 John Wiley & Sons, Ltd.

KEYWORDS: Antarctic Peninsula; diatoms; laminated sediments; palaeoceanography; Palmer Deep.

Introduction

Current concerns over rapid climate change have focused research on ultra-high-resolution records of the Earth's climatic history. Antarctica is intrinsically linked to the global ocean and atmosphere system, therefore it is important to understand the impact climate change has on its ice sheets and the positions of its oceanographic currents. The Antarctic Peninsula (AP) is one of the warmest and wettest areas in Antarctica and experiences two distinct climatic regimes, a warmer more maritime region along the Pacific coast and a cooler more continental climate along the east coast (Martin and Peel, 1978). All AP major glaciers ground at or below sea level and are sensitive to environmental change (Domack and McClennen, 1996; Ingolfsson *et al.*, 1998). The peninsula has experienced a 1.0–2.5 °C increase in summer surface air temperatures over the past 50 years (Jones *et al.*, 1993; King *et al.*, 2003), which has resulted in the collapse of Larsen A Ice Shelf in January 1995 (Doake *et al.*, 1998) and Larsen B (eastern Antarctic Peninsula) in March 2002 (Skvarca and De Angelis, 2003). Analysis of marine sediments from this location should reveal a history of the AP deglaciation. This will give an insight into potential future responses of Antarctic ice sheets and sea level to rapid climate change.

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Site and core description

The AP consists mostly of volcanic and plutonic rocks of the Mesozoic–Cenozoic magmatic arc, with fore-arc basin sedimentary rocks on the western side of the peninsula (Pudsey, 2000). The basement of the AP is composed of Carboniferous to Triassic metasedimentary rocks which formed in an accretionary prism (Barker *et al.*, 1991). During the Ocean Drilling Program (ODP) Leg 178 a 50 m diatomaceous marine sediment core was recovered from Palmer Deep (Site 1098), western AP (Fig. 1). Palmer Deep (64°55′ S, 64°25′ W) is a series of three fault-bound basins (Rebesco *et al.*, 1998) on the inner continental shelf on the western side of the AP (Fig. 1). The shelf on which Palmer Deep is located is broader and deeper (average 450 m) than low-latitude continental shelves (Pudsey *et al.*, 1994) and slopes towards the continent owing to a previous glacial overburden and its tectonic setting.

Nutrient-rich water upwells onto the wide shelf and combines with meltwater from seasonal ice to form an environment

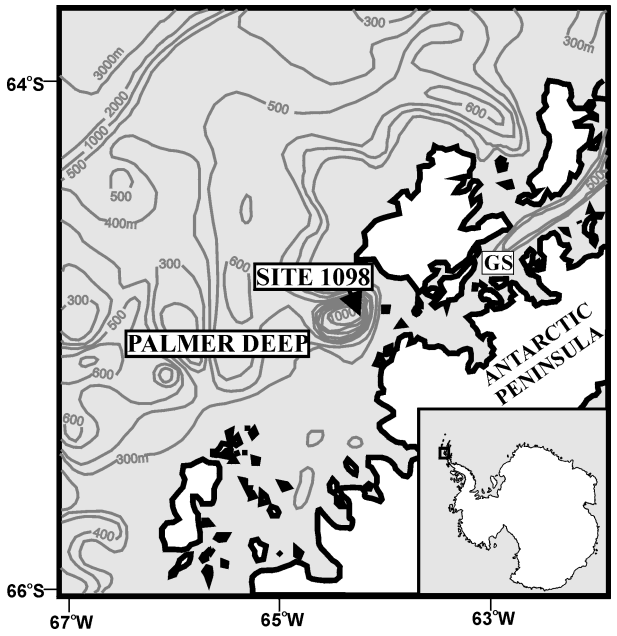


Figure 1 Maps showing the location of Palmer Deep with coarse scale bathymetry (adapted after Barker *et al.*, 1999). GS = Gerlache Strait

where diatoms thrive, making them the most abundant group of microfossils in Antarctic sediments. Palmer Deep acts as a natural sediment trap within this region characterised by extremely high, seasonal productivity (Leventer *et al.*, 1996). The cores from ODP Site 1098 were recovered from a water depth of 1012 m in Basin I, the shallowest of three basins, aligned in an approximately southwest–northeast direction (Kirby, 1993). The sediment recovered consists of olive green homogeneous bioturbated to laminated diatom mud and ooze, with pebbly mud, and muddy diamicton (Barker *et al.*, 1999; Domack *et al.*, 2001). A 4.4 m sequence of laminated sediments, from 45.03 to 40.59 m composite depth (mcd) immediately overlies the glaciomarine diamict (Fig. 2). This investigation aims to use this ultra-high-resolution record from the deglaciation to relate annual, seasonal and sub-seasonal changes in diatom assemblages to oceanographic current positions and ice sheet behaviour.

Radiocarbon dating is complex in the Antarctic due to unusually low radiocarbon (^{14}C) in Antarctic waters. Living organic material has been found to yield anomalously old ^{14}C dates (Andrews *et al.*, 1999; Harris, 2000; Pudsey and Evans, 2001) a phenomenon called the Antarctic reservoir effect. Measured radiocarbon dates must be corrected to account for this reservoir effect and a reservoir correction has been estimated at a value of 1230 yr (Domack *et al.*, 2001) for the Antarctic Peninsula. The deglacial laminated sedimentary sequence from Palmer Deep is dated at 11 460 to 13 180 cal. yr BP (Fig. 2) (Domack *et al.*, 2001).

During the Last Glacial Maximum (LGM) the West Antarctic Ice Sheet (WAIS) extended onto the continental shelf (Bart and Anderson, 1996; Pudsey *et al.*, 1994; Larter and Vanneste, 1995; Anderson *et al.*, 2002; Ingólfsson *et al.*, 2003). Iceberg furrows between 350 and 500 m water depth are evidence of iceberg calving as the ice sheet front retreated (Pudsey *et al.*, 1994). Radiocarbon dating of Palmer Deep sediments by Domack *et al.* (2001) provided constraints on the retreat of the ice sheet at around 13 000 cal. yr BP, which is roughly in agreement with the uncalibrated radiocarbon age of approximately 11 000 yr BP given by Pudsey *et al.* (1994) for the retreat of the ice sheet across the western AP shelf. Currently there are no floating ice shelves north of 69° S on the western side of the AP, and glaciers terminate well within fjords.

Oceanographic setting

General oceanographic conditions for the modern western continental shelf of the AP are dominated by Circumpolar Deep Water (CDW). CDW is found at depths of 1000 m or more in the central Drake Passage and is the most voluminous water mass in the Antarctic Circumpolar Current (ACC) (Sievers and Nowlin, 1984). Within the ACC, the CDW is composed of two types of oceanic water mass, Upper CDW (UCDW) and Lower CDW (LCDW). The core of the LCDW mass is found between 800 and 1000 m at the edge of the continental shelf west of the AP (Smith *et al.*, 1999). The UCDW appears at 200–400 m depth, above the western AP shelf break (Smith *et al.*, 1999). Since the AP continental shelf is relatively deep, the UCDW is an oceanic water mass on the shelf. This UCDW becomes modified on the shelf as it becomes mixed with Antarctic Surface Water (AASW). This modified water supplies heat, salt and low-oxygen water to the west Antarctic Peninsula continental shelf region below 200 m (Smith *et al.*, 1999).

Materials and methods

Materials

Thirty-six sediment slabs, 15 cm long and ~1 cm wide were removed from ODP Cores 178-1098A-6H and 178-1098C-5H using a sediment slab cutter (Schimmelmann, 1990). The slabs were overlapped so the lamination succession could be reconstructed. The slabs were stored in a cold, moist environment in plastic wrap 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).

Backscattered electron imagery (BSEI)

The sediments for polished thin sections were prepared using a fluid displacive resin embedding technique (Pike and Kemp, 1996; Pearce *et al.*, 1998). Thin sections were analysed by backscattered electron imagery (BSEI) using a Cambridge Instruments (LEO) S360 SEM. BSEI highlights the difference in average atomic numbers of the material. Terrigenous grains have relatively high average atomic numbers and this produces bright images. Diatom ooze laminae contain diatom frustules that are filled with low-atomic-number, carbon-based resin which produces dark images. Mosaics of low-magnification images (×20 magnification) were made of each thin section, and laminae thicknesses were measured. Three measurements of lamina thickness are made for each lamina and an average calculated.

Visual inspection of higher magnification images (×100–1000 magnification) allows qualitative analysis of the main diatom species present within the laminae. The mosaics and higher magnification images were used together to determine lamina diatom assemblage composition and the sedimentary fabric.

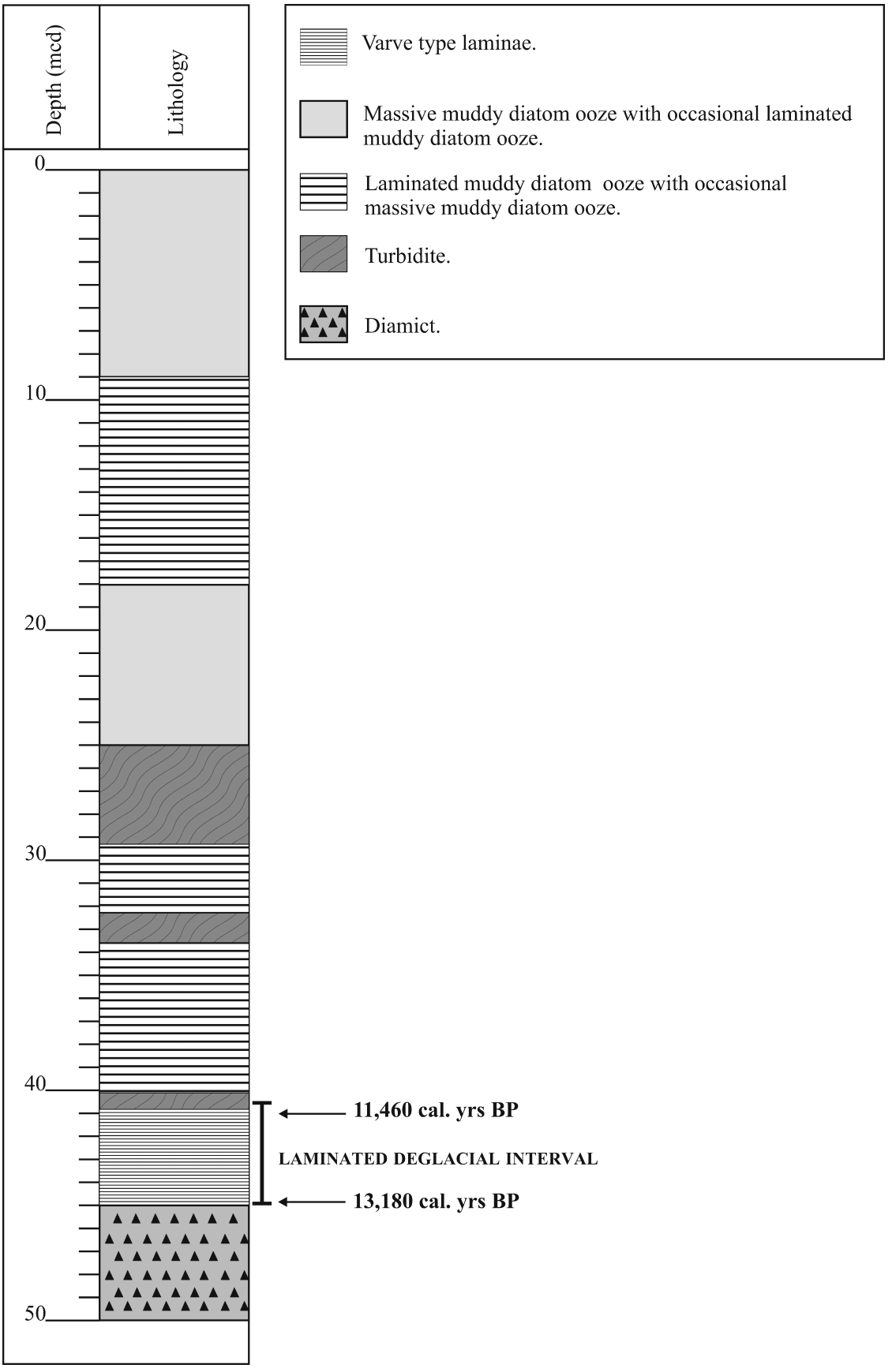


Figure 2 Stratigraphic column for site ODP Site 1098. The deglacial laminated interval (45.03–40.59 mcd) is annotated (adapted after Domack *et al.*, 2001)

Secondary electron imagery (SEI)

Blocks of sediment with dimensions of <0.5 cm were cut from the sediment slabs and fractured to reveal surfaces parallel to the laminated sediment fabric. The blocks of sediment were mounted on standard SEM stubs, left to dry for 24 h and coated in Au–Pd (90:10) for topographic SEI analysis using a Veeco FEI (Philips) XL30 Environmental Scanning Electron Microscope

(ESEM) with FEG (Field Emission Gun). The stubs are related to the concomitant lamina in the BSEI thin section to aid species identification.

Observations

Laminae

The deglacial laminated sequence from 45.03 to 40.59 mcd occurs above a coarse muddy gravel barren of diatoms, a diamicton from the last glacial (Domack *et al.*, 2001) (Fig. 2). The deglacial laminations consist of orange-brown diatom ooze laminae alternating with blue-grey terrigenous laminae (Fig. 3(a)). 191 pairs of these laminations make up the deglacial unit. All observations are made up-core in the deglacial laminated sequence.

Laminae boundaries

Boundaries between the Palmer Deep biogenic and terrigenous laminae occurring between 45.03 and 40.59 mcd are either sharp, bioturbated or gradational. Sharp boundaries are straight with a clear definition between the dark biogenic and light terrigenous laminae (Fig. 4(a)). Bioturbated boundaries are very uneven and patchy, showing redistribution of material from the lower into the upper lamina over 600–1000 μm (Fig. 4(b)). Gradational boundaries occur when the lower and upper laminae colours, diatom species and terrigenous material merge together causing difficult boundary definition (Fig. 4(c)). There does not appear to be a sequence to the different forms of boundaries: all occur intermittently throughout this deglacial laminated interval.

Orange-brown laminae (biogenic)

The orange-brown biogenic laminae consist of almost pure diatom ooze with very little terrigenous material. BSEI photographs of these laminae are dark owing to the high porosity of the diatom ooze (Fig. 3(b) and (c)). Laminations are overwhelmingly near-monogeneric *Chaetoceros* spp. resting spores (CRS) and, to lesser extent, *Chaetoceros* spp. vegetative cells (all *Chaetoceros* mentioned refer to the subgenus *Hyalochaete*). Occasionally more vegetative *Chaetoceros* spp. valves are seen in the SEI stub images than in the BSEI images, relative to CRS, because the fragility of the vegetative remains make identification in BSEI difficult. Other diatom species (*Thalassiosira antarctica*, *Coscinodiscus bouvet*, *Odontella weissflogii*, *Fragilariopsis* spp. and *Corethron criophilum*) are present but in minor amounts. Biogenic lamina thickness ranges from 0.9 to 34.0 mm ($n = 188$ $\sigma = 7.38$ mean = 9.94 mm). A linear regression line plotted on Fig. 5(a) highlights a decrease in biogenic laminae thickness up-core ($r^2 = 0.1747$).

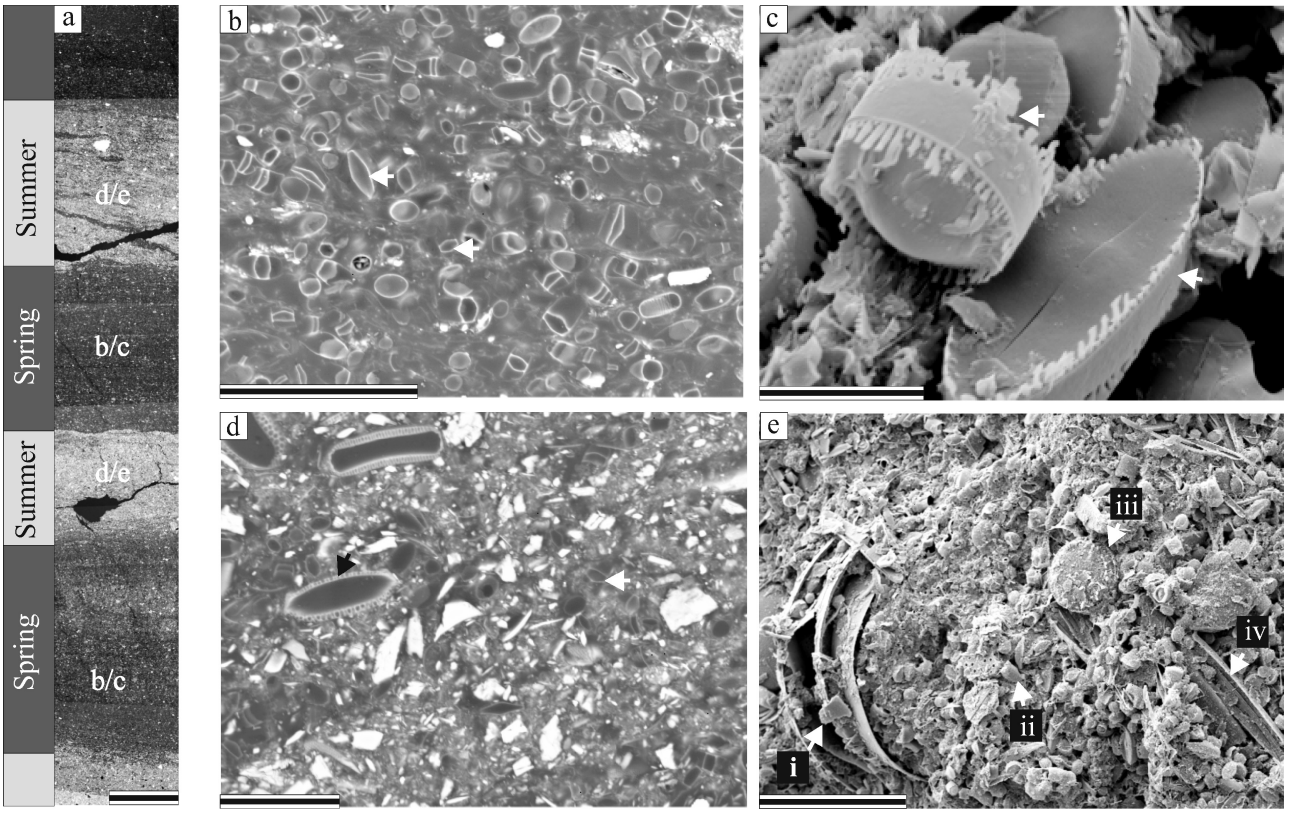


Figure 3 (a) Backscattered secondary electron imagery (BSEI), photomosaic of alternating diatom ooze biogenic laminae (dark: spring) and diatom bearing terrigenous laminae (light: summer) from 42.66 to 42.63 mcd; scale bar 3 mm. (b)/(c) and (d)/(e) refer to annotation on (a). (b) BSEI photograph of diatom ooze biogenic laminae composed of *Chaetoceros* spp. resting spore (white arrows); scale bar 50 μm. (c) Secondary electron imagery (SEI) photograph of *Chaetoceros* spp. resting spores (white arrows) from the biogenic laminae; scale bar 50 μm. (d) BSEI photograph of terrigenous laminae. *Chaetoceros* spp. (white arrow) and *Thalassiosira antarctica* resting spores (black arrows) present. The white fragments are terrigenous material; scale bar 50 μm. (e) SEI photograph of terrigenous laminae with mixed diatom assemblage; scale bar 50 μm. White arrows: (i) *Coscinodiscus bouvet* girdle bands; (ii) *Chaetoceros* spp. resting spores; (iii) *Thalassiosira antarctica* resting spore; (iv) *Fragilariopsis* spp

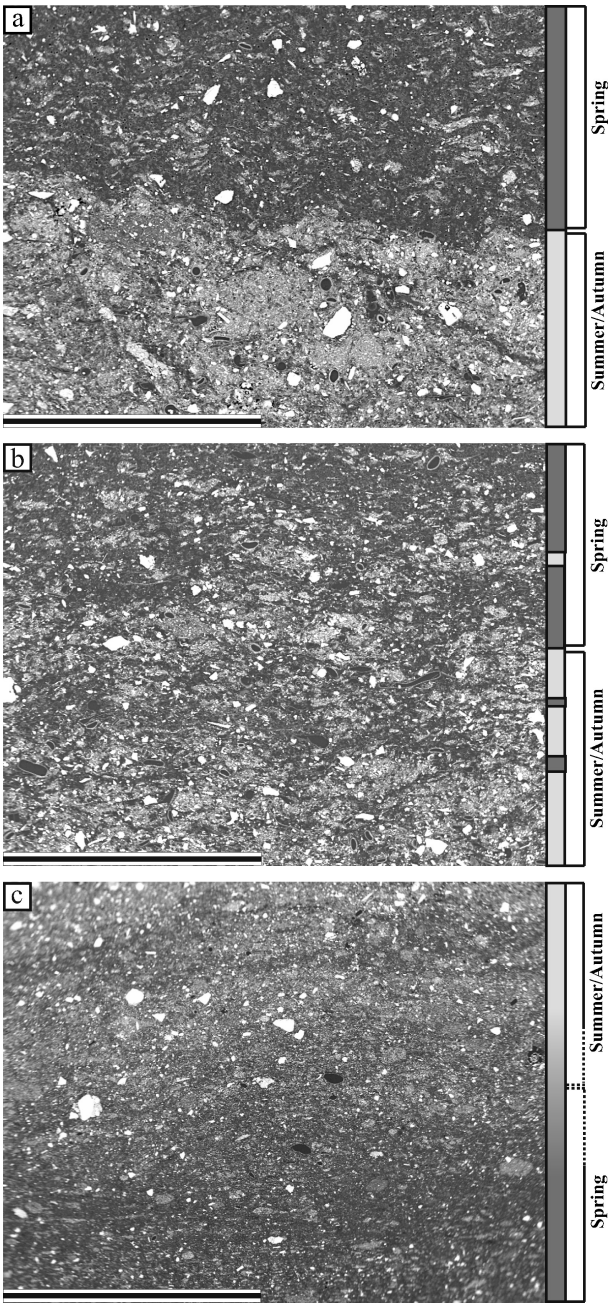


Figure 4 Types of lamina boundaries observed in Palmer Deep deglacial laminated interval (all scale bars 600 μm). (a) Backscattered secondary electron imagery (BSEI) photograph of sharp boundary between summer (terrigenous) and spring (biogenic) laminae. (b) BSEI photograph of bioturbated boundary between summer (terrigenous) and spring (biogenic) laminae. (c) BSEI photograph of gradational boundary between spring (biogenic) and summer (terrigenous) laminae

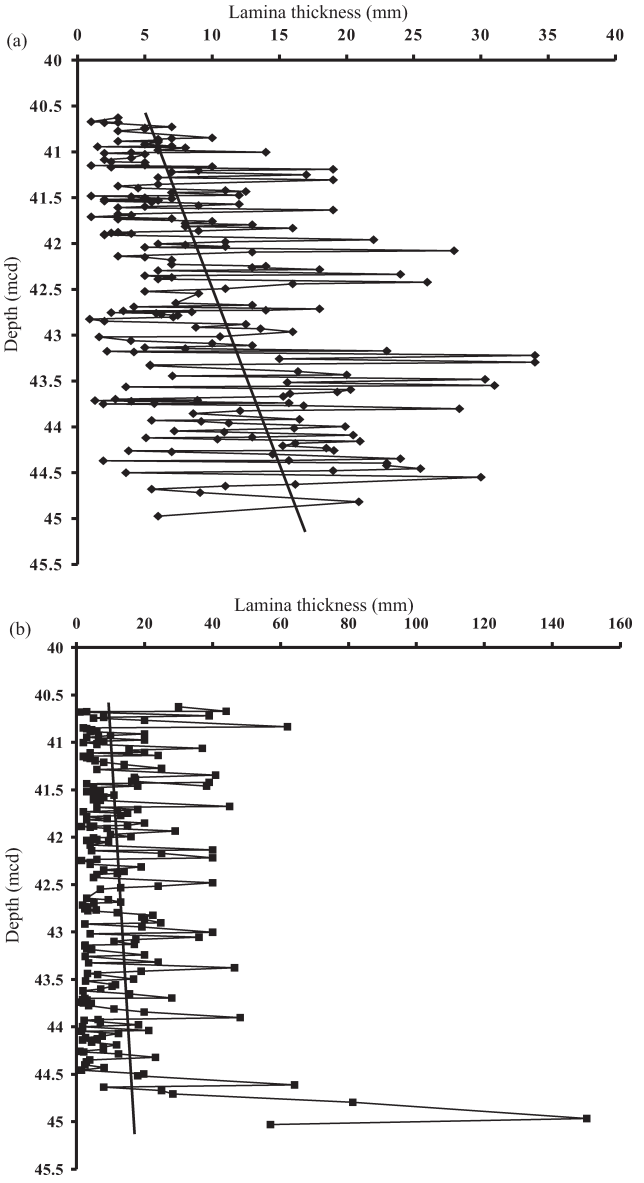


Figure 5 (a) Graph showing biogenic lamina thicknesses through part of the deglacial interval, 40.63–44.97 mcd. Decrease in thickness indicated by regression line ($r^2 = 0.1747$). (b) Graph to show terrigenous laminae thickness through part of the deglacial interval, 40.62–45.03 mcd. Decrease in thickness indicated by regression line ($r^2 = 0.0134$)

Blue-grey laminae (terrigenous)

The blue-grey terrigenous laminae have a greater proportion of terrigenous grains such as ice-rafted silt and clay than the biogenic laminae. The diatom assemblage is near-monogeneric CRS but there is a more abundant minor diatom assemblage than seen in the biogenic laminae (Fig. 3(d) and (e)). This minor assemblage includes the species *C. criophilum*, *C. bouvet*, *O. weissflogii*, *T. antarctica* and *Fragilariopsis* spp. BSEI photographs of these laminae are light owing to the high average atomic numbers of the terrigenous grains. The terrigenous grains range from clay- to sand-size and there is variation in size and amount between laminae. Terrigenous laminae contain more fragmented diatoms than in biogenic laminae. Lamina thicknesses range from 0.95 to 150.1 mm ($n = 191$, $\sigma = 16.77$, mean = 13.37 mm). A linear regression line plotted on Fig. 5(b) shows a slight decrease in terrigenous laminae thickness up-core ($r^2 = 0.0134$). The thickest terrigenous laminae (>50 mm) are at the base of the sequence between 45.03–44.61 mcd. From 44.60 to 40.61 mcd there appears to be a cyclicity in the occurrence of laminae with thicknesses of 40–50 mm.

Sub-laminae within blue-grey laminae (terrigenous)

Terrigenous laminae in the deglacial laminated interval do not consistently have a homogeneous mixed diatom assemblage. Sub-laminae within the blue-grey terrigenous laminae have

an increased abundance of a specific species relative to the rest of the assemblage. These sub-laminae occur intermittently through the interval.

The most commonly observed species forming sub-laminae is *T. antarctica* resting spores, with 47 appearances within the laminated interval in core 1098A-6H (estimate of 50% *T. antarctica* in sub-lamina from BSEI). The sub-laminae are typically found at the top or just below the top of terrigenous laminae (Figs 6 and 7(c) and (d)). Sometimes more than one sub-laminae of *T. antarctica* occurs within a single blue-grey lamina. Sub-laminae of *T. antarctica* resting spores within terrigenous laminae start to occur at 44.97 mcd (Fig. 8). The first occurrence of CRS sub-laminae (estimate of 25% CRS in sub-lamina from BSEI) within the terrigenous laminae is at 44.82 mcd and they continue to occur irregularly up-core (Fig. 8). Single sub-laminae of the species *O. weissflogii* (estimate of 10% *O. weissflogii* in sub-lamina from BSEI), *C. criophilum* (estimate of 15% *C. criophilum* in sub-lamina from BSEI) and *C. bouvet* (estimate of 10% *C. bouvet* in sub-lamina from BSEI) occur within the terrigenous laminae, but are less common than sub-laminae of *T. antarctica* (Fig. 8). The first occurrence of *C. criophilum* sub-laminae (Fig. 7(e) and (f)) within terrigenous lamina is at 44.81 mcd (Fig. 8). Up-core, sub-laminae of *C. criophilum* occur with sub-laminae of *T. antarctica* resting spores, and at 43.22 mcd with *C. bouvet*, *O. weissflogii* and *T. antarctica* sub-laminae (Fig. 8). The first occurrence of *O. weissflogii* sub-laminae (Fig. 7(a) and (b)) within the terrigenous laminae is at 44.49 mcd (Fig. 8). At 43.52 mcd *O. weissflogii* resting spore sub-laminae start to occur together with *T. antarctica* resting spore sub-laminae, and at 43.12 mcd are found with sub-laminae of *T. antarctica*, *C. criophilum* and *C. bouvet* (Fig. 8). Sub-laminae of *C. bouvet* (Fig. 7(g) and (h)) first occur at 44.49 mcd with *T. antarctica* and *O. weissflogii* resting spore sub-laminae (Fig. 8). This type of sub-laminae does not reappear until 43.18 mcd where it occurs several times with other sub-laminae (Fig. 8).

Sub-seasonal and seasonal relationship

Terrigenous laminae with one sub-lamina start at 44.97 mcd and sporadically appear up-core. Terrigenous laminae with two sub-laminae appear at 44.62 mcd and continue to appear irregularly up-core. These sub-laminae are composed of combinations of the following species: *T. antarctica*, *C. criophilum*, *C. bouvet* and *O. weissflogii*. Between 43.22 and 42.72 mcd there are several terrigenous laminae with three or four sub-laminae (Figs 6 and 7).

Discussion

Seasonal signal

Spring

The dominant diatom genus in the biogenic orange-brown laminae is *Hyalochaete Chaetoceros*. The *Chaetoceros* genus favours proximity to sea ice (Leventer, 1991; Crosta *et al.*, 1997) and modern sediment trap data from the AP suggests that CRS blooms are associated with the melting of sea ice in the austral spring (Leventer, 1991). Therefore the biogenic CRS orange-brown laminae are interpreted as spring deposition. *Hyalochaete Chaetoceros* are colonial centric diatoms which form robust resting spores as a survival strategy to combat

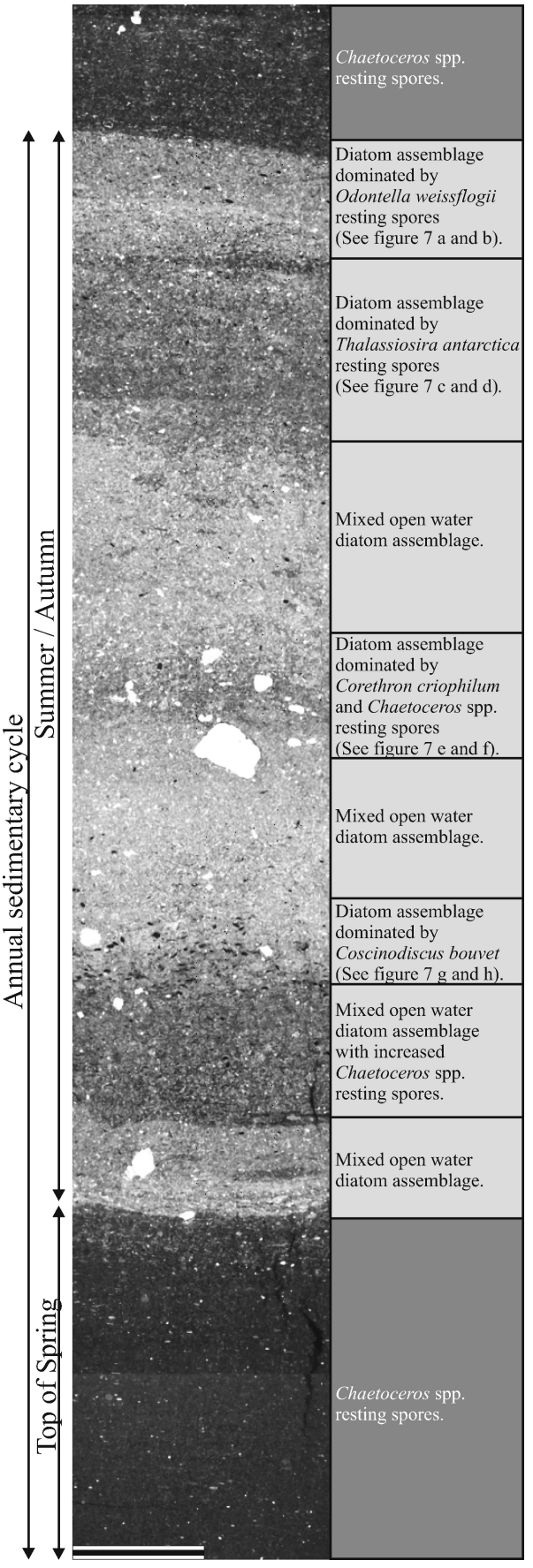


Figure 6 Backscattered secondary electron imagery (BSEI) photomosaic of sub-laminae within the terrigenous laminae (43.11–43.09 mcd); scale bar 3 mm

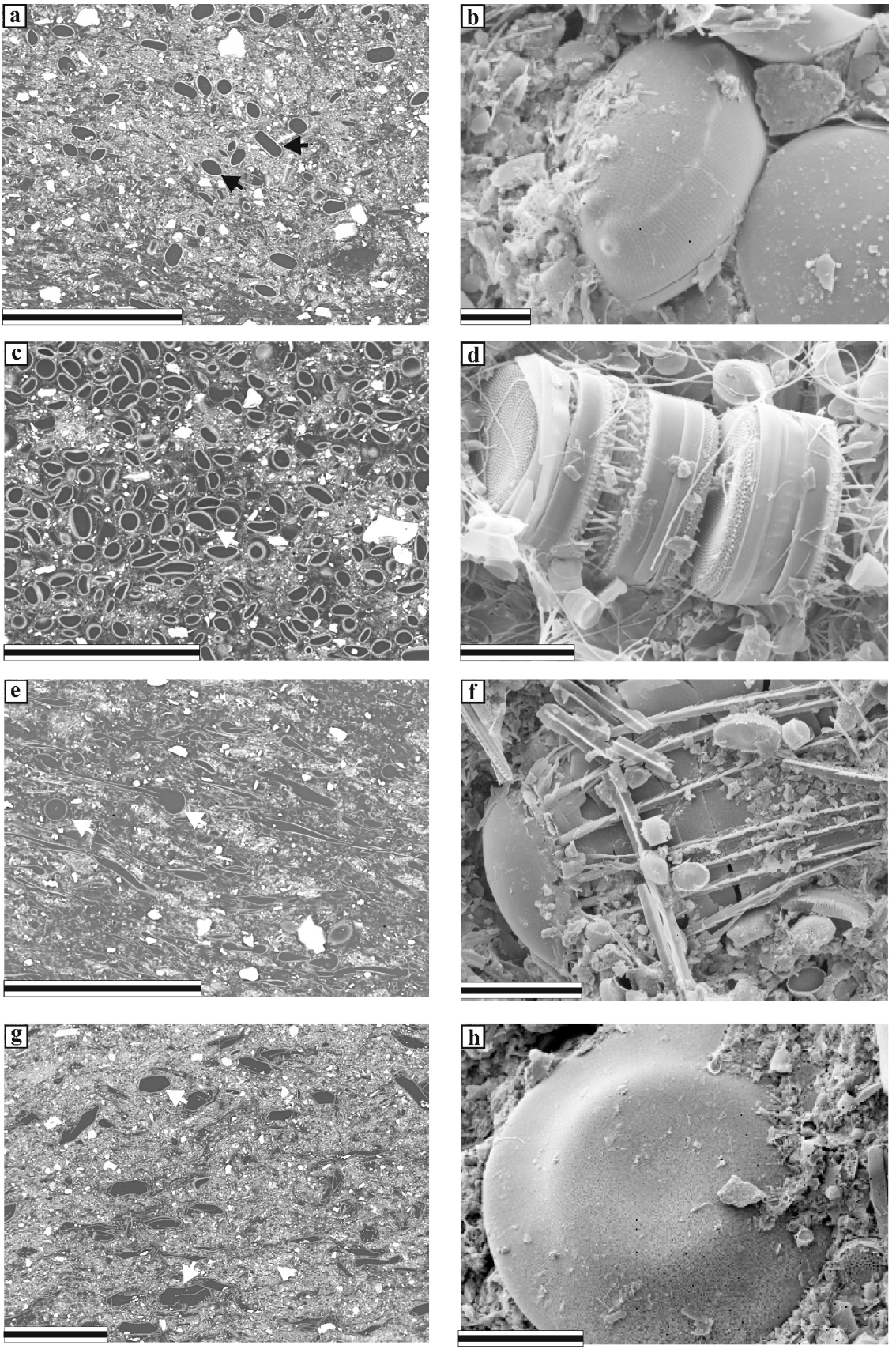


Figure 7 Sub-laminae species associated with Fig. 6. (a) Backscattered secondary electron imagery (BSEI) photograph of *Odontella weissflogii* (black arrows) sub-lamina (scale bar 300 μm). (b) Secondary electron imagery (SEI) photograph of *O. weissflogii* sub-lamina (scale bar 10 μm). (c) BSEI photograph of *Thalassiosira antarctica* resting spore (white arrow) sub-lamina (scale bar 300 μm). (d) SEI photograph *T. antarctica* resting spore sub-lamina (scale bar 20 μm). (e) BSEI photograph of *Corethron criophilum* (white arrows) sub-lamina (scale bar 200 μm). (f) SEI photograph of *C. criophilum* sub-lamina (scale bar 20 μm). (g) BSEI photograph of *Coscinodiscus bouvet* (white arrows) sub-lamina (scale bar 300 μm). (h) SEI photograph of *C. bouvet* (white arrows) sub-lamina (scale bar 50 μm)

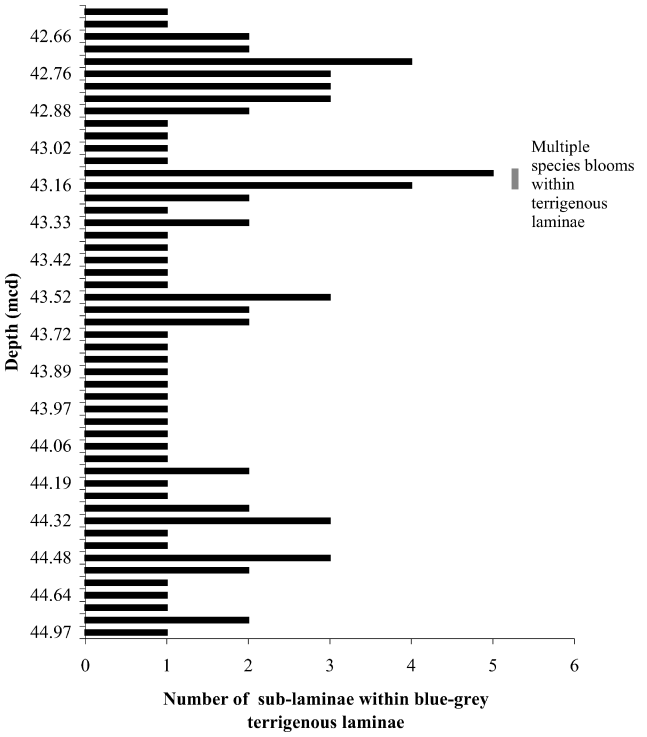


Figure 8 Location of sub-laminae (increased abundance of specific species) within the blue-grey terrigenous laminae in the deglacial laminated interval (45.03–42.52 mcd)

environmental stress such as nitrogen depletion or reduced light conditions. The heavily silicified frustule allows the resting spores to sink and remain dormant until conditions become more favourable and mixing events resuspend them, seeding new populations of vegetative cells (Hargraves and French, 1983). If the resting spores reach the sea floor and either become part of the sediment, or are subjected to anoxic conditions, or eaten by zooplankton, they are lost from the life cycle.

During the deglaciation the water column in the vicinity of the Palmer Deep would be influenced by the adjacent ice sheet. Melting of the sea ice and ice sheet in spring releases freshwater, creating a stratified water column. At this time the Gerlache Strait (Fig. 1) remained largely blocked by ice, preventing the northward flow of surface water as it exists here today (Sjunneskog and Taylor, 2002). The restricted flow would have further enhanced surface water stratification. These conditions of reduced surface salinity and high nutrients associated with melting ice create ideal conditions for high productivity of *Chaetoceros* spp. Environmental stress is likely to occur at the end of spring when nutrients have been used up or when a storm mixes up the water column (breaking down stratification) increasing the salinity and decreasing the temperature of the shelf waters.

Several processes allow vegetative cells to be deposited in the sediment: some living, actively photosynthesising, diatoms can form aggregates by producing sticky transparent gels. This accelerates sinking rates and efficiently exports diatoms from the surface to the sea floor, termed self-sedimentation (Alldredge and Gotschalk, 1989; Grimm *et al.*, 1997). These flocs can also reach the sea floor as parts of marine snow (Alldredge and Gotschalk, 1989) and vegetative cells can be eaten by zooplankton and excreted in faecal pellets.

We suggest that the thickness of the biogenic laminae (Fig. 5(a)) was controlled by the proximity of the West Antarctic Ice Sheet (WAIS) front during the deglacial retreat. As the ice sheet became increasingly distal from Palmer Deep, i.e. nearer to the continent, a decrease in the ice sheet meltwater flux would have led to a less stratified water column and reduced nutrients, therefore reduced productivity created thinner laminae through time.

At the base of the deglacial laminated interval, between 44.82 and 45.03 mcd, there is one biogenic laminae 6 mm thick within 207 mm of terrigenous sediment. This implies that deposition was still dominated by a glacial environment with low productivity (low nutrient concentrations due to low levels of ice melt). The biogenic lamina would have been deposited when the sea ice melted in spring; however, the sea ice may not have melted every year during the early part of the deglaciation.

Summer

As a grounded ice sheet moves, sand, silt and clay are entrained. The sand, silt and clay are transported to the grounded margin by ice streams, the finer fraction becoming suspended in the water column following ice melt and deposited in the sediment (Leventer *et al.*, 2002; Domack *et al.*, in press). The high proportion of ice-rafted material in the mixed diatom assemblage terrigenous lamina is therefore interpreted as summer/autumn melt and deposition.

The species within the summer laminae such as *T. antarctica*, *O. weissflogii*, *C. criophilum* and *C. bouvet* are considered to be open-water diatoms and are related to ice-free, lower nutrient conditions which would have occurred following total melt of seasonal sea ice (Fryxell and Hasle, 1971; Makarov, 1984; Leventer and Dunbar, 1987; Priddle and Thomas, 1989; Zielinski and Gersonde, 1997). The genus *Thalassiosira* is widespread in Antarctic waters and commonly occurs in sea temperatures of −2 to 1 °C (Zielinski and Gersonde, 1997). It has been considered rare to find *T. antarctica* in sea ice (Fryxell and Kendrick, 1988; Leventer and Dunbar, 1987; Zielinski and Gersonde, 1997), which has been attributed to its inability to survive the low light intensities beneath and within sea ice (Fryxell *et al.*, 1987). There is little documented on the ecology of the *Odontella* genus; however *O. weissflogii* is considered endemic to the Southern Ocean and occurs in Antarctic nearshore regions where water temperatures are between −2 and 5 °C (Zielinski and Gersonde, 1997). *C. criophilum* is a very common lightly silicified Antarctic species which occurs in open water with little sea ice (Fryxell and Hasle, 1971; Makarov, 1984; Leventer and Dunbar, 1987) although it has been reported as a component of the ice-edge phytoplankton (Marra and Boardman, 1984). *C. criophilum* usually reaches its highest concentrations along the Antarctic coast and can dominate the phytoplankton (Sommer, 1991; Ligowski *et al.*, 1992). *C. bouvet* is a large distinctive Antarctic endemic species and has a circumpolar distribution. It is found in the neritic environment (coastal habitat) but has been seen in the Scotia Sea (oceanic waters) (Priddle and Thomas, 1989); however, little more is known about the ecology of *C. bouvet*.

In Fig. 5(b), a general decrease in the thickness of the terrigenous laminae could be explained by the shoreward retreat of the melting glacial ice, the source of the terrigenous component. Up-core there are several repeated peaks of relatively thick terrigenous laminae (∼40 mm) (Fig. 5) which could indicate summers with much higher melting or longer seasons. These peaks are not regular, they have a periodicity ranging from 13 to 28 couplets (a minimum of 13 to 28 summers) which does not appear to correlate with modern climate cycles known to affect AP sea ice distribution such as Antarctic Circumpolar Wave (ACW) or El-Niño (Harangozo, 2000).

The terrigenous lamina thicknesses (Fig. 5) do not decline smoothly up-core which implies that the ice sheet did not melt at a continuous rate through the deglaciation. Post-deglaciation, the terrigenous laminae become rarer up-core into the Holocene as the glacial margin became land-based (Leventer *et al.*, 2002). Fragmented frustules observed in the terrigenous laminae are produced as a result of grazing zooplankton, which excrete the remains as faecal pellets, and minor frustule dissolution in the surface waters before sedimentation.

Winter

An abrupt transition from summer terrigenous laminae to the spring biogenic laminae suggests an abrupt change in sediment regime. The decrease in temperatures in winter would increase sea ice cover causing the input to the sediment to dramatically decrease (Gilbert *et al.*, 2003)—the hiatus between summer and spring could even represent several years, particularly in the early deglacial, owing to sea ice cover not melting.

Annual signal

From the onset of deglaciation the orange-brown diatom ooze laminae have been seen to alternate with the blue-grey diatom-bearing terrigenous sediment. These discrete laminae are interpreted as spring and summer/autumn respectively. Sea ice cover in winter prevents sediment flux and deposition (Leventer *et al.*, 2002). Rhythmic couplets observed in the deglacial sediment sequence represent an annual cycle with the base of spring laminae marking the start of a year.

Sub-seasonal signal

The sub-seasonal diatom blooms (Figs 6 and 7) seen within some terrigenous laminae suggest an evolution of the environment and/or shelf waters in deglacial summers. The intact nature of the diatoms within the sub-laminae suggests rapid flocculation and consequent mass sinking at bloom termination events.

Sub-laminae of CRS tend to be observed near the base of the terrigenous laminae (Fig. 6). The sub-laminae are unexpected, since this genus is considered to be associated with spring productivity. The occurrence as sub-laminae could indicate a brief return to water column stratification caused by the last fragments of sea ice melting or an influx of meltwater from the land allowing this genus to bloom and produce the increase in CRS.

C. bouvet sub-laminae (Figs 6 and 7(g) and (h)) are observed in the lower to middle part of the terrigenous laminae. The sub-laminae were probably caused by water column mixing (e.g. storms) in the summer.

The sub-laminae of *C. criophilum* (Figs 6 and 7(e) and (f)) are observed in the middle of terrigenous laminae. The sub-laminae are unusual since high abundances of this species are rarely found in sediments (Taylor and Sjunneskog, 2002). *C. criophilum* 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).

The *O. weissflogii* resting spore sub-laminae (Figs 6 and 7(a) and (b)) seen near the top of the terrigenous laminae were most likely to have been deposited owing to a change in water column conditions. Froneman *et al.* (1997) reported *O. weissflogii* to be a temperate neritic species that is transported into Antarctic waters by unusual, southern intrusions of sub-Antarctic surface waters. The end of summer bloom of this species could therefore have been advected into the Palmer Deep region during a period of maximum cyclone activity (King *et al.*, 2003).

T. antarctica resting spore sub-laminae (Figs 6 and 7(c) and (d)) are seen as one or two bloom events near the top of the terrigenous laminae, acting as a marker for the end of the summer season. Since *T. antarctica* sub-laminae are not observed in the biogenic laminae, we believe that *T. antarctica* blooms in the summer/autumn rather than at the beginning of spring. An increase in salinity as ice forms retards the species growth (Aletsee and Janhnke, 1992) and this intolerance becomes greater as the temperature decreases (Grant and Horner, 1976; Aletsee and Janhnke, 1992). The annual sea ice advance, decreased light intensities (Taylor, 1999) and the brine rejection would have caused convective overturning and mixing, decreasing the nutrients in the water. Therefore, the *T. antarctica* resting spores probably formed at the end of the summer as a result of environmental stress caused by sea ice formation.

The sequence of CRS sub-lamina followed by *C. bouvet*, *C. criophilum*, *O. weissflogii* and *T. antarctica* sub-laminae within one terrignous lamina has been observed several times in the deglacial laminated interval. This suggests that there was a repeated evolution of shelf water conditions during the summers which contain the sub-laminae.

Sub-seasonal and seasonal relationship

The sub-seasonal laminae of increased abundance of specific species, relative to the remaining assemblage, within the terrigenous laminae start occurring near the base (44.97 mcd, Fig. 8) of the deglacial laminated interval. There does not seem to be a periodicity to the occurrence of sub-seasonal blooms in the deglacial interval. Several mechanisms for the multiple sub-seasonal laminae are suggested below, including (1) high tides (2) high cyclone intensity and (3) intrusion of Circumpolar Deep Water (CDW) onto the continental shelf.

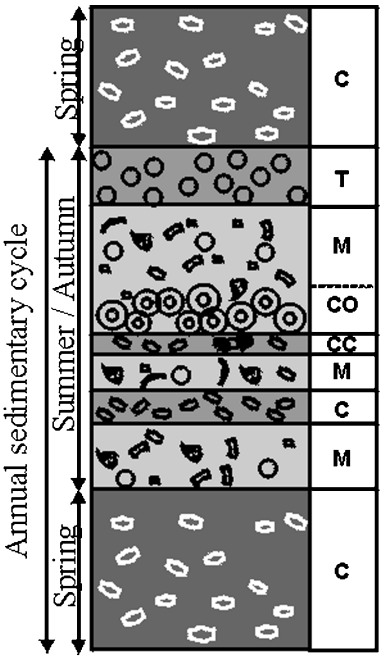
1 A similarity between the alternating laminations and tidal signals and a strong bi-annual control on biogenic and terrigenous laminae deposition has been suggested by Domack *et al.* (2003). A brief period of higher tides in the summer or the increase in autumnal tide amplitude could create conditions which would induce the repeated sub-lamina monospecific blooms seen within some of the terrigenous laminae (Fig. 5). The high tides could bring coastal diatom blooms up against a frontal zone produced by estuarine (meltwater) flow (Leventer *et al.*, 2002). This oceanographic salinity barrier would cause environmental stress inducing the diatoms to rapidly form resting spores. The high density of the frustules would cause them to sink and be deposited on the sea floor. Repeated high tide pulses throughout the summer/autumn would bring different species blooms against the 'barrier', causing the repeated diatom blooms found within the sediment.
2 The Antarctic Peninsula is the most northerly part of the continent and is most subject to mid-latitude oceanographic and atmospheric influences. The peninsula forms the southern boundary to the Drake Passage and is therefore subject to many consequences of this constriction of the Southern

Ocean. The AP is in close proximity to the Antarctic Circumpolar Current. The Circumpolar Trough (CPT), a low-pressure system, encircles Antarctica and in the austral summer is found to be extreme off West Antarctica, cutting the AP at its halfway point near Marguerite Bay (Simmonds, 2003). High cyclone frequencies have a tendency to be found in the regions of the deeper parts of the CPT. In both summer and winter the number and intensity of cyclones are at a maximum west of the AP (King *et al.*, 2003). The presence of large numbers of cyclones to the west of the Peninsula means that the region is subject to very high temporal variability on a wide range of timescales from synoptic to interdecadal (Simmonds and Murray, 1999). Consequently a variety of air trajectories reach the AP and manipulate surface water masses, pushing diatoms against the meltwater-created salinity barrier, causing diatoms to sink and begin resting spore formation. Therefore another possible cause for the multiple sub-laminae could be storms. More storms or a storm of certain intensity or certain direction may cause several blooms to be advected into the Palmer Deep region during the summer, such as *C. bouvet* (Priddle and Thomas, 1989) and *O. weissflogii* (Froneman *et al.*, 1997).

3 A change in oceanographic conditions such as nutrients, water temperature and salinity could influence the occurrence of different diatom species blooms and/or the form of deposition. Domack *et al.* (1992) observed the intrusion of CDW onto the west AP continental shelf to be associated with a major coastward bend in the 3000-m depth contour. This intrusion would introduce a new set of shelf water conditions. Ice melting has been suggested as the driving force behind CDW across-shelf transport (Potter and Paren, 1985). As ice melts, more buoyant, less saline water is released at the surface, this flows outwards drawing the CDW up onto the shelf. This system would have a self-perpetuating circulation because the relatively warm waters of the CDW would melt the ice. A seasonal and interannual variability in the frontal boundary between the ACC and Weddell Sea Transitional Water (more saline water mass from northwestern Weddell Sea) has been observed in the AP region (Hofmann and Klinck, 1998). The boundary ranges from the southern Bransfield Strait into the southern Gerlache Strait. Any impingement of the boundary position onto the continental shelf controls the upwelling of UCDW and resultant changes to shelf waters which could enhance multiple species blooms throughout the summer.

Between 43.16 and 43.09 mcd there is an increase in sub-seasonal laminae within terrigenous laminae (e.g. Fig. 6). It is possible that a threshold in tidal amplitudes, cyclone intensity or intrusion of CDW was reached to produce higher productivity and more multiple sub-seasonal laminae per year.

A schematic model of the resulting deposition is presented in Fig. 9. We believe the CRS, *C. bouvet* and *C. criophilum* sub-laminae were caused by a breakdown in the stratification of the water column. The *O. weissfloggii* sub-lamina was caused by advection of waters into the Palmer Deep region which was followed by a seasonal-change-induced *T. antarctica* sub-lamina.



C	*Chaetoceros* spp. resting spores
T	*Thalassiosira antarctica* resting spores.
M	Mixed open water diatom assemblage
CO	*Coscinodiscus bouvet* and/or *Odontella weissflogii* resting spores.
CC	*Corethron criophilum*

Figure 9 Schematic representation of the sub-seasonal sub-laminae within the terrigenous laminae. Compiled from BSEI data

Conclusions

The Palmer Deep deglacial laminated interval has given an insight into seasonal and sub-seasonal variability within a period of rapid climate change, which has implications for understanding the effect of current warming experienced on the Antarctic Peninsula. The deglacial sedimentary interval consists of laminae or thin beds of orange-brown diatom ooze alternating with blue-grey terrigenous sediments. These result from seasonal depositional events. CRS overwhelmingly dominate the orange-brown laminae and result from early spring sedimentation associated with stratified surface waters and a freshwater cap, trapping nutrients and promoting exceptionally high primary productivity. Productivity decreased during deglaciation as the West Antarctic Ice Sheet (WAIS) retreated. A more open-water Antarctic diatom assemblage (e.g. *C. criophilum*, *C. bouvet* and *T. antarctica*) characterises the blue-grey terrigenous-rich laminae, which result from summer/autumn sedimentation associated with increased terrigenous input, and relate to ice-free, more open water, lower nutrient conditions following total melt of seasonal sea ice. The terrigenous laminae thickness decreases unevenly up-core, suggesting the melting ice sheet retreated shoreward in pulses during the deglaciation. Sea-ice cover in the winter prevents any sedimentation.

During the deglaciation, sub-seasonal summer diatom blooms are observed. High abundances of CRS, *C. bouvet*, *C. criophilum*, *O. weissflogii* and *T. antarctica* relative to the remaining assemblage are observed repeatedly through the summer laminae, suggesting changes in shelf waters throughout the summer. Starting from the base of the summer laminae, a

sequence of sub-laminae species has been ascertained: *Chaetoceros* spp. resting spores, *C. bouvet*, *C. criophilum*, *O. weissflogii* and finally *T. antarctica*. High tides in austral summer and autumn and high cyclone intensity are proposed as possible causes that could have introduced conditions which enhanced specific species productivity. However, we believe the most likely cause of the multiple sub-seasonal bloom laminae is the upwelling of Circumpolar Deep Water (CDW) induced by the sub-seasonal variation in the impingement of ACC onto the continental shelf. After the collapse of the glacial ice sheet, oceanographic and biological systems responded rapidly, early on in the reinstatement of UCDW upwelling onto the continental shelf. By understanding the behaviour of these systems during the last deglaciation, a better understanding has been gained of how they may respond to future periods of rapid climate change. During rapid climate warming and ice sheet collapse, initially high primary production and associated carbon dioxide drawdown may act to produce local cooling and retardation of ice sheet retreat for a number of decades; however, the oceanic and atmospheric circulation systems quickly re-establish to enhance warming of the western Antarctic Peninsula.

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