

Late Quaternary palaeoenvironments in Prydz Bay, East Antarctica: interpretations from marine diatoms

FIONA TAYLOR* and AMY LEVENTER

Department of Geology, Colgate University, Hamilton, NY 13346, USA

**Current address: Institute of Antarctic and Southern Ocean Studies, University of Tasmania, GPO Box 252-77, Hobart, TAS 7001, Australia*

Fiona.Taylor@utas.edu.au

Abstract: Fossil diatom-bearing marine sediment cores recovered from Prydz Channel, Prydz Bay, record episodes of glacial advance and retreat in the bay. Diatom frustules are abundant, well preserved, and the species composition is diverse in two biogenic sediment units composed of siliceous diatom ooze (SMO-1 and SMO-2). Between SMO-1 and SMO-2 a terrigenous unit (T) is present, composed of muddy diamicton and sandy silty clay, which contains poorly preserved rare diatoms. The SMO units are interpreted to represent an open marine setting with seasonal sea ice cover; the T unit is interpreted to represent glacial ice expansion from the Amery Ice Shelf over the site. Based on an age model developed previously for other cores from Prydz Channel with analogous stratigraphies, we interpret our record to be late Quaternary through Holocene in age. The T unit records the Last Glacial Maximum (LGM) in Prydz Bay; the SMO-1 and SMO-2 units record interstadial episodes that are post- and pre-LGM respectively. Extinct diatom taxa in the T and SMO-2 units indicate reworked sediment sourced from two different-aged deposits. Our results provide both a new interpretation of late Quaternary deposition in Prydz Channel and support for previous studies in this region.

Received 8 August 2002, accepted 7 July 2003

Key words: Antarctica diatoms, Holocene, Last Glacial Maximum, Pleistocene

Introduction

Prydz Bay, in East Antarctica, and its adjacent continental rise are key areas for understanding the history of Antarctic glaciation (O'Brien *et al.* 1999a). Yet in comparison to West Antarctica, the history of the East Antarctic coastal margin is relatively unknown. A marine geological and geophysical survey of the East Antarctic margin was conducted in January–March 2001 with the objective of developing a record of climate and oceanographic changes in this region during the late Quaternary. The research will contribute to the development of an integrated model of circum-Antarctic Quaternary climate history.

Here we interpret the depositional history of Prydz Channel, in western Prydz Bay, using fossil diatoms in sediment cores recovered during the survey. Diatoms are sensitive indicators of change within their environment and have proved to be a valuable tool in Antarctic palaeoclimate reconstruction (e.g. Leventer *et al.* 1996, Crosta *et al.* 1998, Cunningham *et al.* 1999, Taylor *et al.* 2001). Prydz Channel is ideal for a study such as this as it is a major depocentre in Prydz Bay, and previous studies have indicated that the channel contains a detailed record of glacial and marine deposition since the late Quaternary (Domack *et al.* 1998). The data presented here builds upon earlier work by Pushina *et al.* (1997), Domack *et al.* (1998), and O'Brien *et al.* (1999b), and provides new insights into the depositional environment of Prydz Bay during the late Quaternary.

Study area

Prydz Bay is the largest embayment in the Indian sector of the Southern Ocean. It is located between 69°E and 80°E, and bounded to the south-east by the Ingrid Christensen Coast and to the west by Mac. Robertson Land (Fig. 1). The southern apex of Prydz Bay, at 70°S, is bordered by the Amery Ice Shelf–Lambert Glacier ice drainage system (AIS). The AIS drains approximately 14% of the East Antarctic Ice Sheet (Hambrey *et al.* 1991), and its repeated advance and retreat across the bay during the Cenozoic has helped to shape the morphological features of the continental shelf in this region (O'Brien & Harris 1996, O'Brien *et al.* 1999a). One of the largest bathymetric features in Prydz Bay is the Amery Depression, which occupies the inner reaches of the bay and descends to depths of about 800 m.

Extending north-west from the Amery Depression is a series of deep trenches that form Prydz Channel (Fig. 2). The channel is 150 km wide (O'Brien *et al.* 1999b) and stretches from the depression to the continental shelf edge. It separates the shallow Fram Bank and Four Ladies Bank, which flank the western and eastern sides of Prydz Bay respectively. At its northern end, Prydz Channel “bulges” seaward into a trough mouth fan on the edge of the shelf (Shipboard Scientific Party 2000). The fan has been the major depocentre for Prydz Channel sedimentation since ice streams first cut the channel in the late Miocene or Pliocene

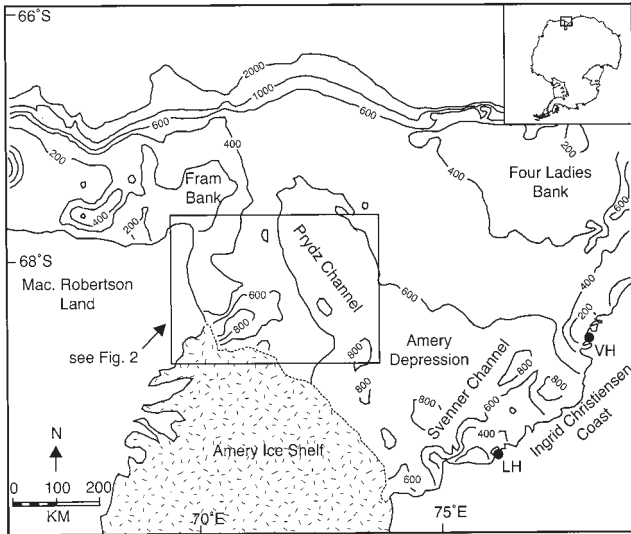


Fig. 1. Location map of Prydz Bay, in relation to the Antarctic continent, and the major oceanographical and geographical features mentioned in the text. Bathymetric contours in metres. VH = Vestfold Hills. LH = Larsemann Hills.

(Leitchenkov *et al.* 1994, O'Brien & Harris 1996). The AIS partly advanced across the continental shelf during the Last Glacial Maximum (LGM) - grounded ice was not present within Prydz Channel, but an ice shelf extended across it (Domack *et al.* 1998). As the AIS retreated after the LGM ice grounding-zone moraines (Fig. 2) were left on the floor and flanks of Prydz Channel (O'Brien *et al.* 1999b).

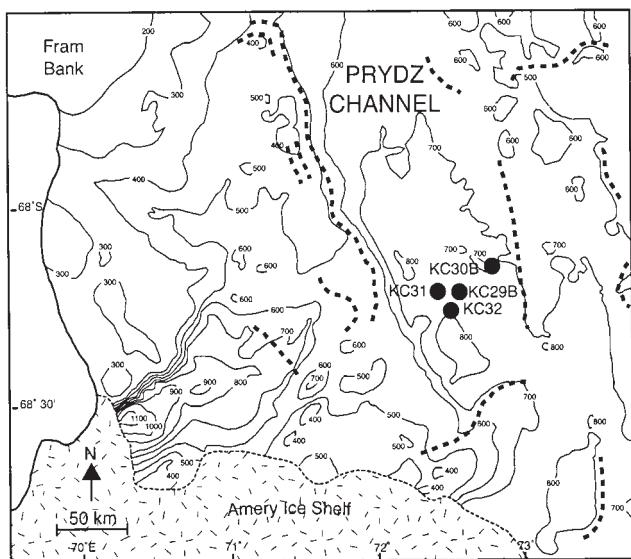


Fig. 2. Detailed bathymetric map of Prydz Channel, indicating the location of kasten cores (KC29B, KC30B, KC31, KC32) analysed for this study. Dashed lines indicate major grounding line "moraines." Bathymetric contours in metres. (Map and grounding lines adapted from Domack *et al.* 1998).

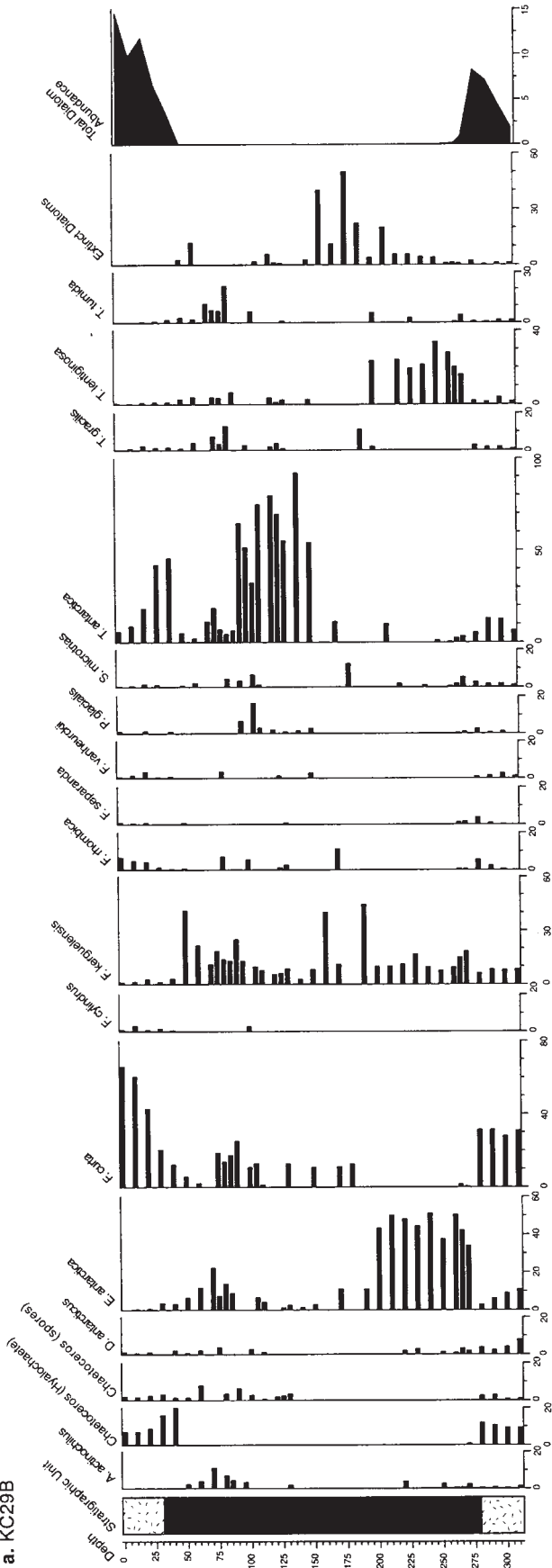
Materials and methods

Four short (*c.* 3.0 m) kasten cores (KC29B, KC30B, KC31, and KC32) were recovered from Prydz Channel during a marine geoscience cruise aboard the RVIB *Nathaniel B. Palmer* in January–March 2001 (cruise number NBP01-01). The cores were photographed, described, and sampled for diatoms on board. The stratigraphy of each core is similar and presented here as a simple biogenic/terrigenous model (Fig. 3a–d): a biogenic unit composed of siliceous muddy ooze (SMO-1) overlies a terrigenous unit (T). The T unit is composed of glacial sediment, either as structureless muddy diamicton and sandy silty clay (KC29B and KC30B; eastern Prydz Channel), or as a granulated facies that overlies sandy mud and sandy clay (KC31 and KC32; western Prydz Channel). A second biogenic unit (SMO-2) composed of siliceous diatom clay occurs below the T unit in KC29B. The sediment stratigraphy is similar to that described in other short gravity cores recovered from Prydz Channel previously (Pushina *et al.* 1997, Domack *et al.* 1998).

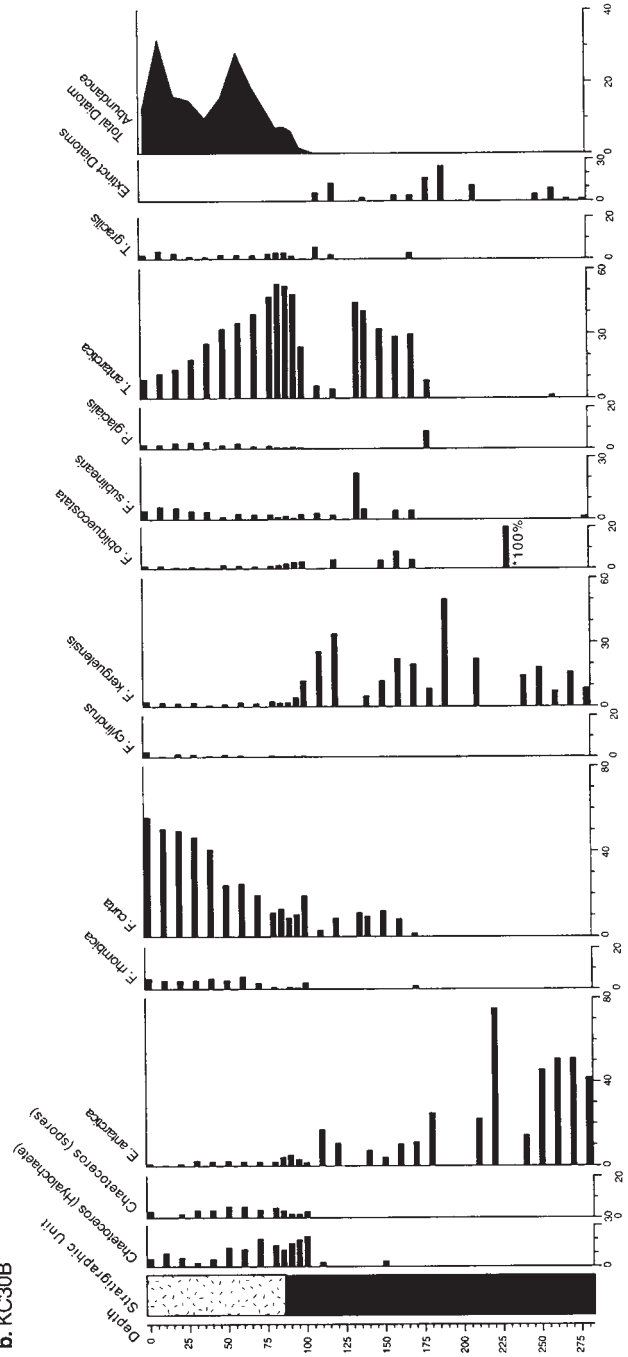
Sediment samples were collected from each core at 5–10 cm intervals by the shipboard scientific party, and prepared later for diatom analysis using the random settling technique described by Scherer (1994). Permanent glass slides were mounted in Norland Optical Adhesive 61 (refractive index 1.56) and cured under a UV light. Quantitative counts were conducted on a Jenaval ausJENA microscope at the University of Nebraska-Lincoln. Traversing each slide horizontally, at least 300 intact diatom frustules were counted at 1000x magnification, using an oil immersion objective lens, from the SMO units. Diatoms were rare in the T unit, and entire slides were scanned at 312.5x or 250x magnification to count all intact frustules. Frustules were considered "intact" when > 50% of the frustule was present. For elongate species (i.e. *Pseudonitzschia* Peragallo, 1900, *Thalassiothrix* Cleve et Grunow, 1880, *Trichotoxon* Reid et Round, 1980) only end pieces were counted, then divided by two at the end of each slide. Whole *Chaetoceros* Ehrenberg, 1844 resting spores were multiplied by two; half spores were counted as one. Vegetative *Chaetoceros* cells were classified into the subgenera *Phaeoceros* and *Hyalochaete*. *Dactyliosolen antarcticus* Castracane, 1886 girdle bands were counted as one, although it is uncertain how many of these represent an entire cell. Total diatom abundance was calculated as valves per gram of dry sediment ($v\ gds^{-1}$) and plotted down core (Fig. 3a–d).

Biostatistical analyses were used to compare the differences in extant diatom abundance and diversity between SMO-1 and SMO-2 from KC29B. A Student's *t*-test was used to calculate the difference in mean abundance. The two-tailed, unpaired test was performed using GraphPad Prism version 3.0 for Macintosh. A Shannon-Wiener diversity index was used to calculate the difference in diversity, and a *t*-test used to determine

a. KC29B



b. KC30B



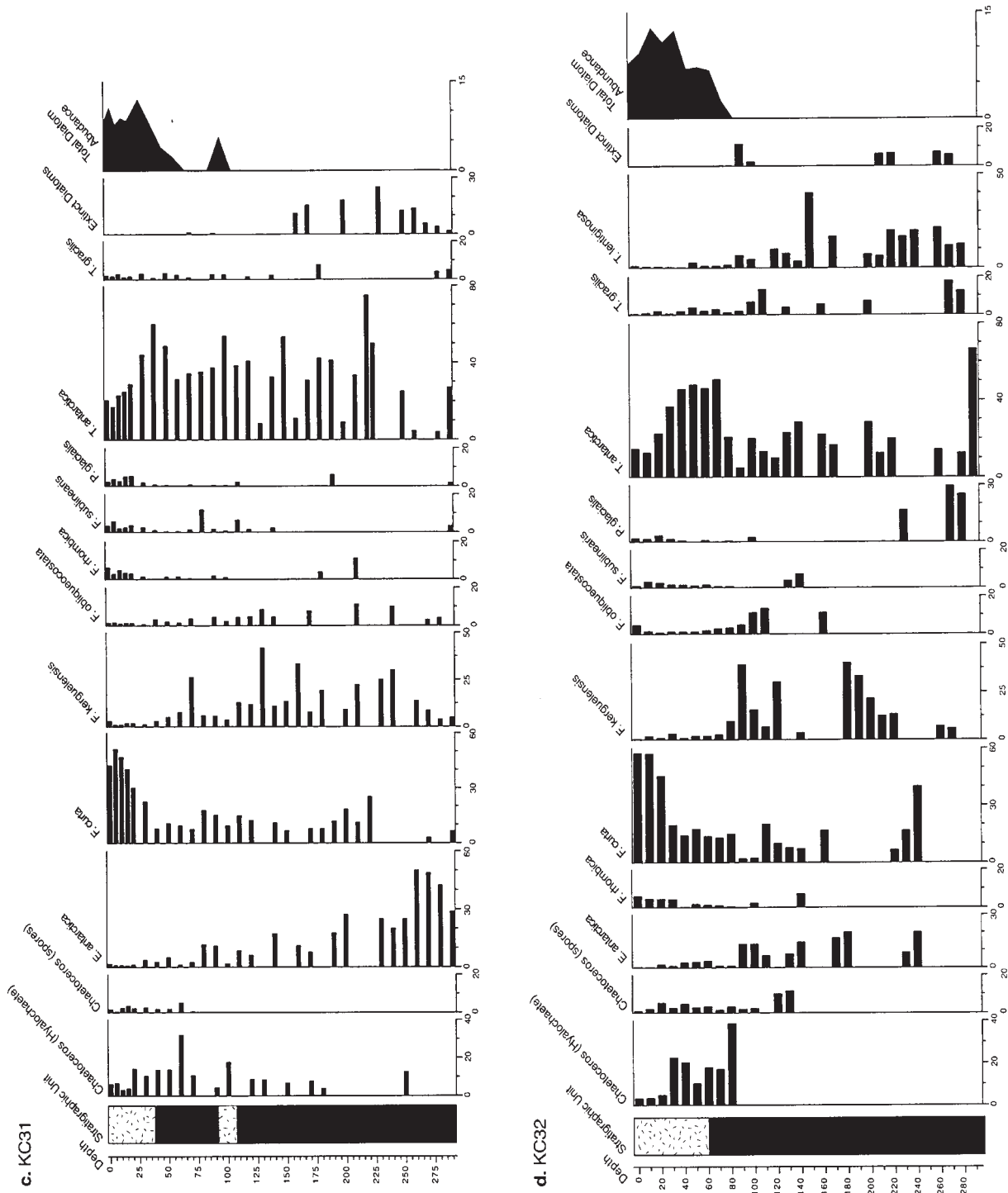


Fig. 3. Stratigraphical units, distribution of common ($\geq 2\%$) extant diatoms (%), total extant diatoms (%), and total diatom abundance (valves per gram of dry sediment [$v\ gds^{-1}$] $\times 10^6$) in Prydz Channel cores: **a.** KC29B, **b.** KC30B, **c.** KC31, **d.** KC32. Depth in centimetres. Stratigraphical unit symbols: SMO-1 and SMO-2 (speckled), T (solid). Note: abundance of *F. obliquecostata* in KC30B at 230 cm equals 100%, KC31 sample illustrated at 225 cm collected at 222 cm.

Table I. Extinct diatom taxa observed in Prydz Channel cores.

Taxon	Core			
	KC29B	KC30B	KC31	KC32
<i>Actinocyclus ingens</i> Rattray, 1890	*			*
<i>Actinocyclus karstenii</i> Van Heurck, 1909				*
<i>Denticulopsis</i> sp. cf. <i>vulgaris</i> (Okuno) Yanagisawa et Akiba, 1990	*	*	*	*
<i>Hemidiscus karstenii</i> Jousé, 1962	*			
<i>Pyxilla</i> Greville, 1865	*		*	*
<i>Rouxia</i> Brun et Heribaud, 1893	*	*		
	(SMO-2 only)			
<i>Stellarima stellaris</i> † (Roper) Hasle et Sims, 1986				*
<i>Stephanopyxis</i> Ehrenberg, 1845	*			*
<i>Thalassiosira inura</i> Gersonde, 1991	*	*	*	*
<i>Thalassiosira torokina</i> Brady, 1977	*	*		*

† *Stellarima stellaris* is extinct in Antarctic waters but occurs elsewhere in the world today.

whether the difference was significant (Zar 1996). The Shannon-Wiener index combines two quantifiable measures: species richness (the number of species in the sample) and species equitability (how even are the numbers of individuals of each species) to calculate diversity (the distribution of observations among categories).

Results

Diatom abundance and diversity

Diatoms are abundant and well preserved in SMO-1 (Fig. 3a–d). Diatom total mean abundance in this unit is highest in the eastern Prydz Channel core KC30B (14.96×10^6 v gds⁻¹). From the other cores, diatom abundance in SMO-1 is slightly less; KC29B (10.64×10^6 v gds⁻¹), KC31 (9.01×10^6 v gds⁻¹) and KC32 (9.19×10^6 v gds⁻¹). The maximum total abundance also occurs in KC30B at 10 cm (31.57×10^6 v gds⁻¹).

A bi-modal abundance distribution pattern is present in SMO-1 in KC30B, KC31 and KC32. In each core diatom abundance increases below the core top to form two peaks in abundance. Abundance then decreases rapidly where the sediment grades from SMO-1 to the T unit. In KC31 a third peak in abundance is observed at 100 cm (5.54×10^6 v gds⁻¹); the peak corresponds with a 14-cm diatom mud layer between a sandy sediment layer. In KC29B, diatom abundance decreases below the core top, from a maximum value at 0 cm (14.51×10^6 v gds⁻¹), then increases to a peak at 20 cm (11.77×10^6 v gds⁻¹) before decreasing rapidly again over the boundary where SMO-1 grades into the T unit.

In SMO-2 from KC29B, diatom total mean abundance (5.45×10^6 v gds⁻¹) is almost half that observed in SMO-1 for the same core. Based on the two-tailed *t*-test, however, the difference in abundance is considered to be not quite statistically significant ($P = 0.0560$). A comparison of the mean abundance per gram of sediment for each extant species between SMO-1 and SMO-2, using the Shannon-Wiener index and *t*-test, also indicates that there is no

significant difference in diatom diversity between the two sediment units from this core ($t_{0.05(2), 13.21 \times 10^6} = 1.9600$).

Extant diatom assemblages

The diatom assemblages in SMO-1 are similar throughout the Prydz Channel cores. The pennate sea ice diatom *Fragilariopsis curta* (van Heurck) Hustedt, 1958 is the most abundant species in the upper 15 cm (KC31), 20 cm (KC29B and KC32) and 40 cm (KC30B), and forms 40–60% of the assemblage. The abundance of *F. curta* decreases down core and there is a corresponding increase in resting spores of *Thalassiosira antarctica* var. *antarctica* Comber, 1896, a centric neritic diatom. The spores replace *F. curta* as the most abundant taxon with depth in all cores. In KC31, the transition from *F. curta* to *T. antarctica* dominance occurs at 20 cm, where each is co-dominant. *Thalassiosira antarctica* spores are most abundant below 30 cm (KC29B, KC31, KC32) and below 50 cm (KC30B), forming 31–60% of the assemblage. In KC32, vegetative *Chaetoceros* (subgenus *Hyalochaete*) spp. are dominant at 80 cm, forming 39% of the diatom assemblage. The *Hyalochaete* assemblage is not observed in the other cores, but this may reflect sampling resolution as their abundance does increase with depth in all cores before the sedimentary transition from SMO-1 to the T unit. In KC30B and KC31, *Hyalochaete* and *T. antarctica* spores are co-dominant at 100 cm and 60 cm, respectively, before the transition from SMO-1 to the T unit.

The SMO-2 in KC29B is dominated by *Eucampia antarctica* var. *recta* (Mangin) Fryxell et Prasad, 1990 from 265–270 cm, which forms up to 42% of the diatom assemblage. Below 280 cm, *F. curta* is the most abundant species, forming 28–31%. Diatom abundance, diversity and degree of preservation in SMO-2 is similar to that observed in SMO-1, except for the greater abundance of heavily silicified extant frustules and the presence of extinct diatom taxa.

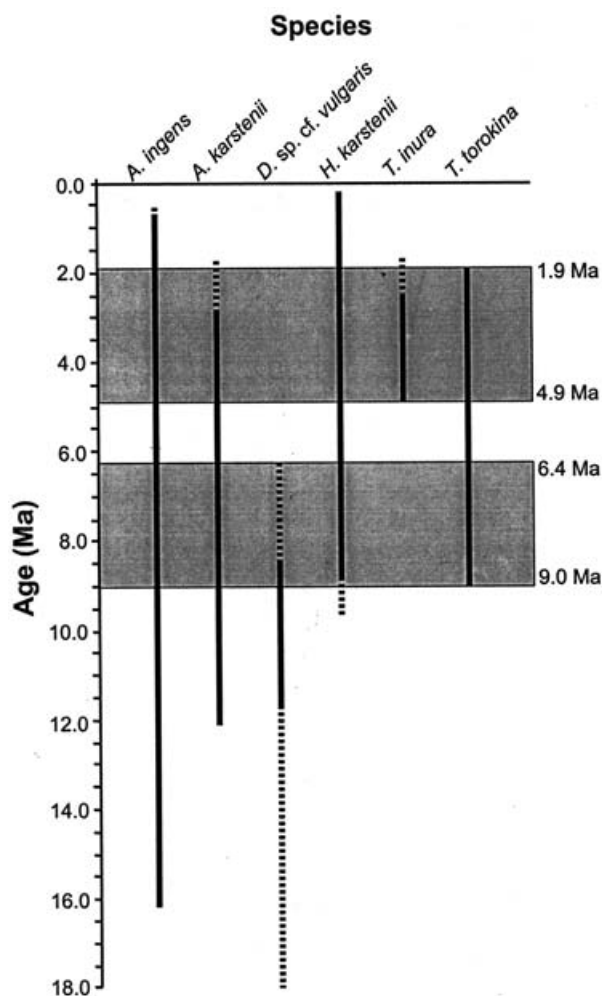


Fig. 4. Biostratigraphical age ranges of extinct diatom taxa that occur in the Prydz Channel cores. Data based on Barker *et al.* (1999) and Whitehead *et al.* (in press). Shaded areas represent the two different ages for the reworked sediment (1.9 to 4.9 Ma and 6.4–8.5 to 9.0 Ma) as the ages ranges of *D. sp. cf. vulgaris* and *T. inura* do not overlap.

Extinct diatom taxa

Extinct diatom species and extant taxa that no longer inhabit Antarctic waters are present in the SMO-2 and T units (Table I). Based on the first and last appearance data and first common occurrence data of biostratigraphical marker species (Barker *et al.* 1999, Whitehead *et al.* in press), the extinct taxa indicate that reworked sediment in both stratigraphical units has been sourced from deposits of two different ages: 1.9 to 4.9 Ma and 6.4–8.5 to 9.0 Ma (Fig. 4).

Discussion

We are confident that the stratigraphical units in our cores match those described and radiocarbon dated in other cores from Prydz Channel (Pushina *et al.* 1997, Domack *et al.* 1998). The analysis of fossil marine diatoms here provides

both new interpretations and support for the previous authors' interpretations of the late Quaternary depositional environment in Prydz Channel.

Late Pleistocene / Last Glacial Maximum

Diatoms are rare in the terrigenous unit, where they occur in trace abundance as large, heavily silicified taxa (e.g. *Fragilariopsis kerguelensis* (O'Meara) Hustedt, 1952, *Thalassiosira lentiginosa* (Janisch) Fryxell, 1977, the winter form of *E. antarctica* var. *recta*, and extinct taxa) (Table I). The frustules of both extant and extinct taxa are poorly preserved - most valves occur as fragments - which suggests that they have undergone extensive mechanical damage and dissolution during deposition and/or at the sediment–water interface. The biostratigraphically mixed taxa indicate that sediment reworking has occurred.

Pushina *et al.* (1997) hypothesized that the diamicton in their "Unit II" from Prydz Channel was late Pleistocene in age. The radiocarbon dates from poorly sorted diamicton described in Domack *et al.* (1998), analogous to Pushina's Unit II and our T unit, confirmed the hypothesis, indicating that the sediment is c. 20.0–11.0 Ka. Based on rare neritic and sub-Antarctic ocean diatoms (similar to our findings) and benthic and planktic calcareous foraminifera representative of lower latitudes (also noted by Domack *et al.* 1998) in the diamicton, Pushina *et al.* (1997) concluded that the unit was deposited in a warmer environment than currently exists in Prydz Bay. (Their conclusion does not appear to consider that the enclosing glaciogenic sediments are probably indicative of colder conditions than today.) O'Brien & Harris (1996) and Domack *et al.* (1998) interpreted the unit to be of glacial marine origin, as radiocarbon dates from within this unit correlated with the LGM. The LGM is recognized globally as the peak of the last climatic cooling and glacial ice advance, which in Antarctica is placed between 25.0–10.0 kyr BP (Adamson & Pickard 1986). In the North Atlantic the LGM started and ended abruptly 24.0–18.0 Ka (Bard 1999), but in Antarctica the glacial ice that extended offshore during the LGM did not begin to retreat from most coastal margins until 17.0–14.0 Ka (Ingólfsson *et al.* 1998). In Prydz Bay and the surrounding coast there is evidence for LGM ice advance (e.g. Bird *et al.* 1991, Roberts & McMinn 1999, Taylor & McMinn 2002), which included an expansion of the AIS, and its associated subsystems, across Prydz Channel. The AIS grounded along the channel's eastern and western peripheries (Domack *et al.* 1998, O'Brien *et al.* 1999b), but deposition in front of the grounding line was dominated by iceberg rafting (Domack *et al.* 1998). Based on diatom analysis alone we cannot interpret the origin of the T unit further than Domack *et al.* (1998) or O'Brien *et al.* (1999b), but suggest the rare reworked species in the T unit support the previous authors' interpretations that it is of glacial origin.

Holocene open marine sedimentation

The diatom-rich biogenic unit, SMO-1, lies directly above the diatom-poor glacially derived T unit. Domack *et al.* (1998) also identified SMO-1 in Prydz Channel (hence we have adopted their terminology); SMO-1 is analogous to Pushina's *et al.* (1997) "Unit 1." Uncorrected radiocarbon dates indicate that SMO-1 was deposited after the LGM and spans the Holocene epoch, from 12.7 ¹⁴C Ka to 2.5 ¹⁴C Ka (Domack *et al.* 1998). The siliceous muddy ooze is typical of glacial marine sediment deposited on the Antarctic continental shelf today (Anderson *et al.* 1980, Domack 1988), and is indicative of open-marine conditions with seasonal sea ice cover (Domack *et al.* 1991). The diatom data presented both in our study and in Pushina *et al.* (1997) support the interpretation of open marine sedimentation; diatom abundance increases rapidly and frustules are well preserved across the stratigraphical boundary where SMO-1 replaces the T unit. Within the SMO-1 diatom assemblages, however, we have identified three depositional periods:

- 1) a period characterized by vegetative *Chaetoceros* spp. (subgenus *Hyalochaete*), at the onset of SMO-1 deposition,
- 2) a climatically warm, stable period with high, but variable, primary productivity and an influx of oceanic taxa, and
- 3) a cooler period with increased sea ice diatoms at the top of SMO-1.

Where SMO-1 replaces the T unit the abundance of *Chaetoceros* spp. (*Hyalochaete*) is relatively high; this trend continues halfway up SMO-1 in all cores. *Chaetoceros* typically bloom in spring (Kemp *et al.* 2000), and in the Southern Ocean both vegetative cells and resting spores occur in greatest abundance in the sediment where surface water temperatures are -1° to 1°C (Zielinski & Gersonde 1997). The palaeoenvironmental signal of *Chaetoceros* in Antarctic records is unclear (Zielinski & Gersonde 1997), although in a temperate Canadian fjord *Chaetoceros* has been found to be indicative of cool, nutrient-rich, well-mixed waters (Hobson & McQuoid 2001). Similar conditions may have prevailed in Prydz Channel following the onset of open marine deposition after LGM ice shelf retreat. The age for the transition from grounded ice shelf conditions east of Prydz Channel to initial open marine conditions is 11.0 ¹⁴C Ka (O'Brien & Harris 1996). It is interesting to note that the abundance of *Chaetoceros* resting spores does not increase appreciably in the Prydz Channel cores immediately after open marine deposition commenced. Retreat of the AIS would have likely resulted in an influx of fresh water in the vicinity of Prydz Channel. Previous studies have indicated that such influxes produce stratified surface waters suitable for diatom blooms, which are followed by mass spore production (Leventer 1992,

Leventer *et al.* 1996, Crosta *et al.* 1997, Taylor & McMinn 2001, Sjunneskog & Taylor 2002). Yet there is no evidence in our data to indicate elevated spore formation following AIS retreat. Absence of *Chaetoceros* spore layers in Prydz Channel could be an artefact of our sampling resolution and/or low age resolution of the sediment.

Thalassiosira antarctica resting spores are dominant in the mid sections of SMO-1. The robust spores are common in fossil diatom assemblages from both the East and West Antarctic coastal margins, but the lightly silicified vegetative cells are rarely preserved (based on our own observations). The taxon prefers neritic, mainly open-water habitats where the sea surface temperatures range from -2° to 1°C (Zielinski & Gersonde 1997). Sediment trap data from the Ross Sea suggest that vegetative *T. antarctica* bloom in summer, when open water conditions dominate (Leventer, unpublished data 2001). It is hypothesized that the resting spores develop as a result of low light intensities beneath the summer bloom and/or subsequent nutrient depletion in the water column (Taylor & McMinn 2001). The abundance of *T. antarctica* resting spores in the mid sections of SMO-1, which we interpret to be mid Holocene in age based on the model presented by Domack *et al.* (1998), suggests that the palaeoclimate was warmer and open water more prevalent in Prydz Bay than compared to today. Similar conclusions have been drawn from evidence in other cores from Prydz Bay (Pushina *et al.* 1997, Taylor & McMinn 2001), the continental shelf adjacent to Mac. Robertson Land (Taylor & McMinn 2002), the Ross Sea (Cunningham *et al.* 1999), and the Antarctic Peninsula (Leventer *et al.* 1996, Taylor *et al.* 2001, Taylor & Sjunneskog 2002).

In SMO-1 from the early and mid Holocene we also observe a high abundance of open-water taxa compared to more recent values. The taxa include *F. kerguelensis*, *Thalassiosira lentiginosa*, *T. gracilis* (Karsten) Hustedt, 1958, and *Porosira glacialis* (Grunow) Jørgensen, 1905, which are neritic and/or sub-Antarctic oceanic forms. *Fragilariopsis kerguelensis*, for example, is most abundant in modern diatom assemblages north of the Antarctic Divergence (Pushina *et al.* 1997), prefers sea surface temperatures ranging from 0° to 10°C (Zielinski & Gersonde 1997) and is negatively correlated with sea ice (Burckle *et al.* 1987). Similar observations have been made for *T. lentiginosa* (Zielinski & Gersonde 1997). The increased abundance of open water taxa in Prydz Channel in the early and mid Holocene suggests that warmer surface waters penetrated further into Prydz Bay than they do today. Peaks in diatom total abundance during these times also imply that the climate was warmer and more stable than today, supporting higher primary productivity.

Sea ice diatoms and a reduction in total diatom abundance characterize the uppermost intervals of SMO-1 in all cores, except KC29B. (We are uncertain why KC29B is different, but speculate that some of the core top may have been lost

during core recovery.) Notably in KC30B, KC31, and KC32, *F. curta* replaces *T. antarctica* as the dominant species. *Fragilariopsis curta* is one of the most common species in Antarctic sea ice and is the dominant form in surface sediments from Prydz Bay today where sea ice is present for more than nine months of the year (Taylor *et al.* 1997). The abundance of *Fragilariopsis rhombica* (O'Meara) Hustedt, 1952, *F. sublinearis* (Van Heurck) Heiden, 1928, *F. vanheurckii* (Peragallo) Hustedt, 1958, and *F. cylindrus* (Grunow) Krieger, 1954 also increase towards the top of SMO-1. Each of these species is considered typical of modern and past sea ice and sea ice-edge environments (e.g. Medlin & Priddle 1990, Armand 1997, Zielinski & Gersonde 1997, Gersonde & Zielinski 2000). The diatom data provide evidence for an environment less favourable to primary productivity, increased sea ice cover and decreased volume of warmer surface water penetrating deep into Prydz Bay. The volume of cool water penetrating the bay may have gone unchanged. We infer this period of deposition to represent the late Holocene Neoglacial, based on the Prydz Channel chronology published by Domack *et al.* (1998). The rapid transition from a warm, stable mid Holocene to a cooler late Holocene is recognized widely in both East and West Antarctic records (review in Taylor & Sunneskog 2002).

Pre-Holocene interstadial

SMO-2 is present only in the longest of the four cores analysed (313 cm long KC29B), but this unit has been mapped and dated previously in Prydz Bay (Domack *et al.* 1998). Results from the 1998 study found SMO-2 to be widespread across the 15 000 km² floor of Prydz Channel, and show that it thickens towards the mouth of the channel and to pre-date the LGM. The distribution and character of SMO-2 led Domack *et al.* (1998) to suggest that it was deposited in a sub-ice shelf setting.

We are unable to confirm the sub-ice shelf hypothesis using the diatom data presented here. Based on the *t*-tests and Shannon-Wiener diversity index, neither the differences between the total diatom mean abundance in SMO-1 (10.64×10^6 v gds⁻¹) and SMO-2 (5.45×10^6 v gds⁻¹) nor extant species diversity are statistically significant. If SMO-2 was deposited in a sub-ice shelf environment, away from the ice front where light is limited and water currents are weaker, one would expect diatom abundance and diversity to be low (Kellogg & Kellogg 1988), especially compared to an open marine setting such as that represented by SMO-1. Yet there is no statistical evidence to indicate that the differences in total diatom abundance (a proxy for primary productivity) or extant diatom diversity in SMO-2 and SMO-1 from KC29B are significantly different. It is important to note also that SMO-2 has a higher clay and sand content compared to SMO-1, which is similar to the surface sediments adjacent to the AIS that consist of silty clay

(Quilty 1985) and gravelly muddy sand (Harris *et al.* 1998). These observations suggest that SMO-2 was deposited beyond the floating margin of the AIS.

Of visual importance in the SMO-2 diatom flora is the relatively high abundance of robust extant frustules and presence of extinct taxa. The abundance of robust frustules, particularly over the transitional boundary from SMO-2 to the T unit where *Eucampia antarctica* var. *recta* is dominant, suggests that bottom water currents were strong and winnowed out smaller, fragile frustules during sedimentation. A similar situation exists on the shallow banks in Prydz Bay today, where strong currents remove the fine sediment and fragile diatoms to leave a deposit characterized by sand and the heavily silicified, robust frustules of *E. antarctica* (Taylor *et al.* 1997). The extinct diatom taxa in SMO-2 provide further evidence for sediment reworking. Domack *et al.* (1998) hypothesized that this was most likely contemporaneous with a sea level low stand that permitted iceberg or ice shelf turbation. Icebergs in Prydz Bay today plough the seafloor and ground in water depths < 690 m (O'Brien & Leitchenkov 1997); the cores analysed in our study were recovered from water depths ≥ 740 m. It is possible that a combination of current winnowing by currents and mixing of surface sediments by iceberg ploughing in an environment proximal to the AIS formed the diatom assemblage in SMO-2.

Based on the first and last appearance data of the extinct diatom taxa in the SMO-2 and T units (Fig. 4) it is apparent that the age ranges of at least two species (*Thalassiosira inura* and *Denticulopsis* sp. cf. *vulgaris*) do not overlap. From this we argue that two age ranges are represented (1.9 to 4.9 Ma and 6.4–8.5 to 9.0 Ma) and indicate that the reworked sediment was sourced from different deposits. A likely source of the extinct diatoms in Prydz Channel is from glaciomarine sediments of the Pagodroma Group in the Prince Charles Mountains (Hambrey & McKelvey 2000, McKelvey *et al.* 2001). The Pagodroma Group today occurs up to 500 km inland of Prydz Bay (Whitehead *et al.* 2001) and has been dated as Neogene in age based upon *in situ* and glacially reworked diatoms (Whitehead 2000, McKelvey *et al.* 2001). These deposits could have been transported offshore via the AIS and redeposited in Prydz Bay. Pliocene marine diatom assemblages also occur in the Vestfold and Larsemann Hills adjacent to Prydz Bay (Fig. 1) (McMinn & Harwood 1995, Harwood *et al.* 2000). An alternative hypothesis, but one less favourable, is that the reworked sediment may have been sourced from within Prydz Bay itself. On the outer shelf, diatoms ranging in age from upper Pliocene to extant Quaternary are present, but are in diatom oozes deposited at depths > 100 m below the seafloor (Mahood & Barron 1996, Shipboard Scientific Party 2000). It is unlikely that these could have been reworked into the much shallower sediment, < 5 m below the seafloor, discussed here. Domack *et al.* (1998) noted that there is an abundance of extinct diatoms in near-surface

sediments on the outer reaches of Prydz Channel and hypothesized that these have been re-circulated into the channel via the Prydz Bay gyre, which circulates clockwise around the bay, but they did not indicate from where the reworked near-surface sediments were sourced.

Conclusion

The diatom data presented offers both support for previous sedimentological and palaeoecological studies in Prydz Channel (Pushina *et al.* 1997, Domack *et al.* 1998, O'Brien *et al.* 1999b) and a new interpretation of the late Quaternary depositional environment here. Assuming that the stratigraphical units described in our cores match those described and dated previously from Prydz Channel, the diatom data provides evidence for two interstadials and one episode of glacial ice advance in Prydz Bay during the last c. 22.0 Ka. Diatoms are rare and reworked in the glacially derived terrigenous unit; we interpret the diatoms to have been re-deposited from beneath the AIS during the LGM, which was grounded along the periphery of Prydz Channel but not grounded within the channel. This is in agreement with Domack *et al.* (1998), but both Domack *et al.* (1998) and our studies reinterpret the earlier findings of Pushina *et al.* (1997). Diatoms are abundant and well preserved in SMO-1 and represent deposition in an open marine setting following post-LGM glacial ice retreat. This supports the conclusion of Domack *et al.* (1998) and O'Brien *et al.* (1999b). Within SMO-1, however, we have identified three Holocene depositional environments based on the diatom data:

- 1) a well-mixed and nutrient-rich environment immediately following LGM retreat of the AIS from the Prydz Channel site,
- 2) a warm, relatively stable mid Holocene with increased open-water taxa and high diatom abundance, and
- 3) a cooler late Holocene.

SMO-2 was deposited during a pre-Holocene interstadial, although extinct taxa indicate that the sediment has been reworked. The abundance and diversity of diatoms in SMO-2 is comparable to that in SMO-1 from the same core. We suggest that the SMO-2 diatom flora were deposited proximal to the AIS. These findings represent a preliminary analysis of new data retrieved from the Prydz Bay region. Ongoing sedimentological and geochemical analyses will contribute further to our interpretation of late Quaternary depositional environment in Prydz Channel and its relation to circum-Antarctic climate change.

Acknowledgements

This research was funded by NSF Award OPP-9909367.

The author's wish to thank E. Domack (Hamilton College) for the shipboard core descriptions, N. McClenaghan (Colgate University) for diatom slide preparation, J. Whitehead (University of Tasmania) for biostratigraphical data and extant data identification, D. Harwood (University of Nebraska-Lincoln) for resource support, and the NBP01-01 scientific party and crew. We thank Drs C. Ó Cofaigh and C. Allen for their helpful comments.

References

- ADAMSON, D.A. & PICKARD, J. 1986. Cainozoic history of the Vestfold Hills. In Pickard, J., ed. *Antarctic oasis. Terrestrial environments and history of the Vestfold Hills*. Sydney: Academic Press, 63–93.
- ANDERSON, J., KURTZ, D., DOMACK, E. & BALSHAW, K. 1980. Glacial and glacial marine sediments of the Antarctic continental shelf. *Journal of Geology*, **88**, 399–414.
- ARMAND, L.K. 1997. *The use of diatom transfer functions in estimating sea-surface temperature and sea-ice in cores from the southeast Indian Ocean*. PhD thesis, Australian National University, 392 pp. [Unpublished]
- BARD, E. 1999. Ice age temperatures and geochemistry. *Science*, **284**, 1133–1134.
- BARKER, P.F., CAMERLENGHI, A., ACTON, G.D., *et al.* 1999. *Proceedings of the Ocean Drilling Program, Initial Reports*, **178** [Online]. Available from http://www-odp.tamu.edu/publications/178_IR/178TOC.HTM. [Cited 2003-05-15].
- BIRD, M.I., CHIVERS, A.R., RADNELL, C.J. & BURTON, H.J. 1991. Sedimentological and stable isotope evolution of lakes in the Vestfold Hills, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **84**, 109–130.
- BURCKLE, L., JACOBS, S. & McLAUGHLIN, R. 1987. Late austral spring diatom distribution between New Zealand and the Ross Ice Shelf, Antarctica: hydrographic and sediment correlations. *Micropaleontology*, **33**, 74–81.
- CROSTA, X., PICHON, J.-J. & BURCKLE, L.H. 1998. Application of modern analog technique to marine Antarctic diatoms: reconstruction of maximum sea-ice extent at the Last Glacial Maximum. *Paleoceanography*, **13**, 284–297.
- CROSTA, X., PICHON, J.-J. & LABRACHERIE, M. 1997. Distribution of *Chaetoceros* resting spores in modern peri-Antarctic sediments. *Marine Micropaleontology*, **29**, 283–199.
- CUNNINGHAM, W.L., LEVENTER, A., ANDREWS, J.T., JENNINGS, A.E. & LICHT, K.J. 1999. Late Pleistocene–Holocene marine conditions in the Ross Sea, Antarctica: evidence from the diatom record. *The Holocene*, **9**, 129–139.
- DOMACK, E. 1988. Biogenic facies in the Antarctic glacial marine environment: basis for a polar glacial marine summary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **63**, 357–372.
- DOMACK, E.W., JULL, A.J.T. & NAKAO, S. 1991. Advance of East Antarctic outlet glaciers during the Hypsithermal: implications for the volume state of the Antarctic ice sheet under global warming. *Geology*, **19**, 1059–1062.
- DOMACK, E., O'BRIEN, P., HARRIS, P., TAYLOR, F., QUILTY, P., DeSANTIS, L. & RAKER, B. 1998. Late Quaternary sediment facies in Prydz Bay, East Antarctica and their relationship to glacial advance onto the continental shelf. *Antarctic Science*, **10**, 236–246.
- GERSONDE, R. & ZIELINSKI, U. 2000. The reconstruction of late Quaternary Antarctic sea-ice distribution: the use of diatoms as a proxy for sea ice. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **162**, 264–286.
- HAMBREY, M.J. & MCKELVEY, B.C. 2000. Major Neogene fluctuations of the East Antarctic ice sheet: stratigraphic evidence from the Lambert Glacier region. *Geology*, **28**, 887–890.

- HAMBREY, M.J., EHRMANN, W.U. & LARSEN, B. 1991. Cenozoic glacial record from the Prydz Bay continental shelf, East Antarctica. *Proceedings of Ocean Drilling Program Scientific Results*, **119**, 77–132.
- HARRIS, P.T., TAYLOR, F., PUSHINA, Z., LEITCHENKOV, G., O'BRIEN, P.E. & SMIRNOV, V. 1998. Lithofacies distribution in relation to the geomorphic provinces of Prydz Bay, East Antarctica. *Antarctic Science*, **10**, 227–235.
- HARWOOD, D.M., MCMINN, A. & QUILTY, P.G. 2000. Diatom biostratigraphy and age of the Pliocene Sorsdal Formation, Vestfold Hills, East Antarctica. *Antarctic Science*, **12**, 443–462.
- HOBSON, L.A. & MCQUOID, M.R. 2001. Pelagic diatom assemblages are good indicators of mixed water intrusions into Saanich Inlet, a stratified fjord in Vancouver Island. *Marine Geology*, **174**, 124–138.
- INGÓLFSSON, Ó., HJORT, C., BERKMAN, P.A., BJÖRCK, S., COLHOUN, E., GOODWIN, I.D., HALL, B., HIRAKAWA, K., MELLES, M., MÖLLER, P. & PRENTICE, M.L. 1998. Antarctic glacial history since the Last Glacial Maximum: an overview of the record on land. *Antarctic Science*, **10**, 325–344.
- KELLOGG, T.B. & KELLOGG, D.E. 1988. Antarctic cryogenic sediments: biotic and inorganic facies of ice shelf and marine-based ice sheet environments. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **67**, 51–74.
- KEMP, A.E.S., PIKE, J., PEARCE, R.B. & LANGE, C.B. 2000. The “Fall dump” – a new perspective on the role of a “shade flora” in the annual cycle of diatom production and export flux. *Deep-Sea Research II*, **47**, 2129–2154.
- LEITCHENKOV, G., STAGG, H., GANDJUKHIN, V., COOPER, A.K., TANAHASHI, M. & O'BRIEN, P. 1994. Cenozoic seismic stratigraphy of Prydz Bay (Antarctica). *Terra Antarctica*, **1**, 395–398.
- LEVENTER, A. 1992. Modern distribution of diatoms in sediments from the George V Coast, Antarctica. *Marine Micropaleontology*, **19**, 315–332.
- LEVENTER, A., DOMACK, E.W., ISHMAN, S.E., BRACHFELD, S., MCCLENNEN, C.E. & MANLEY, P. 1996. Productivity cycles of 200–300 years in the Antarctic Peninsula region: understanding linkages among the sun, atmosphere, oceans, sea ice, and biota. *Geological Society of America Bulletin*, **108**, 1626–1644.
- MAHOOD, A.D. & BARRON, J.A. 1996. Late Pliocene diatoms in a diatomite from Prydz Bay, East Antarctica. *Micropaleontology*, **42**, 285–302.
- MCKELVEY, B.C., HAMBREY, M.J., HARWOOD, D.M., MABIN, M.C.G., WEBB, P.-N. & WHITEHEAD, J.M. 2001. The Pagodroma Group - a Cenozoic record of the East Antarctic ice sheet in the northern Prince Charles Mountains. *Antarctic Science*, **13**, 455–468.
- MCMINN, A. & HARWOOD, D.M. 1995. Biostratigraphy and palaeoecology of early Pliocene diatom assemblages from the Larsemann Hills, eastern Antarctica. *Antarctic Science*, **7**, 115–116.
- MEDLIN, L.K. & PRIDDLE, J. 1990. *Polar marine diatoms*. Cambridge: British Antarctic Survey, 214 pp.
- O'BRIEN, P.E. & HARRIS, P.T. 1996. Patterns of glacial erosion and deposition in Prydz Bay and the past behaviour of the Lambert Glacier. *Papers and Proceedings of the Royal Society of Tasmania*, **130**, 79–84.
- O'BRIEN, P.E. & LEITCHENKOV, G. 1997. Deglaciation of Prydz Bay, East Antarctica, based on echo sounder and topographic features. *Antarctic Research Series*, **71**, 109–125.
- O'BRIEN, P.E., COOPER, A.K., RICHTER, C. & BALDAUF, J. 1999a. Ocean Drilling Program Leg 188 Scientific Prospectus. Prydz Bay-Cooperation Sea, Antarctica: Glacial History and Paleoceanography. *Ocean Drilling Program Scientific Prospectus*, **188** [Online]. Available from http://www-odp.tamu.edu/publications/prosp/188_prs/188prosp.pdf [Cited 2002-02-14]
- O'BRIEN, P.E., DE SANTIS, L., HARRIS, P.T., DOMACK, E. & QUILTY, P.G. 1999b. Ice shelf grounding zone features of western Prydz Bay, Antarctica: sedimentary processes from seismic and sidescan images. *Antarctic Science*, **11**, 78–91.
- PUSHINA, Z.V., KOLOBOV, D.D. & DRUZHININA, N.I. 1997. Biostratigraphy and paleoecology of the bottom sediments in Prydz Bay. In RICCI, C.A., ed. *The Antarctic region: geological evolution and processes*. Siena: Terra Antartica Publications, 869–874.
- QUILTY, P.G. 1985. Distribution of foraminiferids in sediments of Prydz Bay, Antarctica. *Special Publication of the South Australian Department of Mines and Energy*, **5**, 329–340.
- ROBERTS, D. & MCMINN, A. 1999. A diatom-based palaeosalinity history of Ace Lake, Vestfold Hills, Antarctica. *The Holocene*, **9**, 401–408.
- SCHERER, R.P. 1994. A new method for the determination of absolute diatom abundance and other silt-sized sedimentary particles. *Journal of Paleolimnology*, **12**, 171–179.
- SHIPBOARD SCIENTIFIC PARTY. 2000. Leg 188 Preliminary Report: Prydz Bay-Cooperation Sea, Antarctica: glacial history and paleoceanography. *Ocean Drilling Program Preliminary Report*, **188** [Online]. Available from http://www-odp.tamu.edu/publications/prelim/188_prel/188prel.pdf [Cited 2002-02-14]
- SJUNNESKOG, C. & TAYLOR, F. 2002. Postglacial marine diatom record of the Palmer Deep, Antarctic Peninsula (ODP Leg 178, Site 1098) I: total diatom abundance. *Paleoceanography*, **17**, art. no. 8003 (DOI: 10.1029/2000PA000563).
- TAYLOR, F. & MCMINN, A. 2001. Evidence from diatoms for Holocene climate fluctuations along the East Antarctic margin. *The Holocene*, **11**, 255–266.
- TAYLOR, F. & MCMINN, A. 2002. Late Quaternary diatom assemblages from Prydz Bay, East Antarctica. *Quaternary Research*, **57**, 151–161.
- TAYLOR, F. & SJUNNESKOG, C. 2002. Postglacial marine diatom record of the Palmer Deep, Antarctic Peninsula (ODP Leg 178, Site 1098) II: diatom assemblages. *Paleoceanography*, **17**. (DOI: 10.1029/2000PA000564).
- TAYLOR, F., MCMINN, A. & FRANKLIN, D. 1997. Distribution of diatoms in surface sediments of Prydz Bay, Antarctica. *Marine Micropaleontology*, **32**, 209–230.
- TAYLOR, F., WHITEHEAD, J. & DOMACK, E. 2001. Holocene paleoclimate change in the Antarctic Peninsula: evidence from the diatom, sedimentary and geochemical record. *Marine Micropaleontology*, **41**, 25–43.
- WHITEHEAD, J.M. 2000. *Cenozoic palaeoenvironment of the Southern Ocean and East Antarctica: geological and palaeontological evidence from the Kerguelen Plateau, Vestfold Hills and Prince Charles Mountains*. PhD thesis, University of Tasmania, 257 pp. [Unpublished]
- WHITEHEAD, J.M., MCKELVEY, B.C. & MCMINN, A. 2001. Cenozoic glacial deposits in the southern Prince Charles Mountains of East Antarctic. *Terra Antarctica*, **7**, 655–656.
- WHITEHEAD, J.M., HARWOOD, D.M., & MCMINN, A. In press. Ice-distal late Miocene marine strata from inland Antarctica. *Sedimentology*, **50**.
- ZAR, J.H. 1996. *Biostatistical analysis*, 3rd ed. Englewood Cliffs, NJ: Prentice Hall, 662 pp.
- ZIELINSKI, U. & GERSONDE, R. 1997. Diatom distribution in Southern Ocean surface sediments (Atlantic sector): implications for paleoenvironmental reconstructions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **129**, 213–250.