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Biogeochemistry of platelet ice: its influence on particle flux under fast ice in the Weddell Sea, Antarctica

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Abstract An array of four sediment traps and one current meter was deployed under a well-developed platelet layer for 15 days in the Drescher Inlet in the Riiser Larsen ice shelf, in February 1998. Traps were deployed at 10 m (just under the platelet layer), 112 m (above the thermocline), 230 m (below thermocline) and 360 m (close to sea floor). There was a substantial flux of particulate organic material out of the platelet layer, although higher amounts were collected in the traps either side of the thermocline. Material collected was predominantly composed of faecal pellets containing diatom species growing within the platelet layer. The size classes of these pellets suggest they derive from protists grazing rather than from larger metazoans. Sediment trap material was analysed for particulate organic carbon/nitrogen/phosphorus (POC/PON/POP) and $\delta^{13}C_{POC}$ (carbon isotopic composition of POC). These were compared with organic matter in the overlying platelet layer and the water column. In turn, the biogeochemistry of the platelet layer and water column was investigated and the organic matter characteristics related to inorganic nutrients (nitrate, nitrite, ammonium, silicate, phosphate), dissolved organic carbon/nitrogen (DOC/DON), pH, dissolved inorganic carbon (DIC), oxygen and $\delta^{13}C_{DIC}$ (carbon isotopic composition dissolved inorganic carbon).

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Introduction

A key aim of the SCAR programme "Ecology of the Antarctic Sea Ice Zone" (EASIZ) is "to determine the role of the sea ice zone on Antarctic marine systems and in the control of global biogeochemical and energy exchanges". A major question being asked by the programme is "what physical, chemical and biological factors determine patterns of production, sedimentation and recycling, and the major elemental budgets, of the Antarctic coastal and shelf system" (SCAR 1994). A critical factor in understanding what happens to the biomass produced within the sea ice is the fate of sea-ice algae and the role they play in the pelagic and in benthopelagic coupling. Sea ice provides a stable environment for primary production and a refuge for metazoans and protozoans which graze on the high algal biomass within the ice or at the ice/water interface (see review by Ackley and Sullivan 1994 and citations therein). On ice breakup, algae contained within the ice may seed the ice-edge bloom after their release into the water column, or can be swiftly transported downwards by the formation of aggregates (Riebesell et al. 1991) and/or packaging into rapidly sinking faecal pellets (González 1992; González et al. 1994).

Although there have been several studies that have linked high productivity in sea ice with increased particle flux and sediment accumulation in regions underlying ice cover (Leventer 1998), we are as yet unable to fully interpret the importance of sea ice in the overall benthopelagic coupling of the Southern Ocean. This applies particularly to the shallow coastal areas where the influence of seasonal inputs of organic matter to the sediments may be highly significant (Gutt et al. 1998 and citations therein).

Diatom frustules compose a large fraction of the material in Antarctic sediments (Zielinski and Gersonde 1997; Leventer 1998), and the heavy silicification of some diatom species such as *Fragilariopsis* species ensures that frustules are well preserved in the sedimentary

record (Smetacek 1999a). The importance of the durability of the frustules of these species for palaeoenvironmental indicators is discussed in the comprehensive review by Leventer (1998). Two species, *Fragilariopsis curta* and *F. cylindrus*, have been shown to be very successful in exploiting sea ice and ice-edge regions and, as such, provide useful proxies for sea-ice distribution. Stable carbon isotopic values of diatoms have been proposed as another paleoenvironmental indicator of sea-ice conditions. Several studies have illustrated an enrichment of ^{13}C in sea-ice diatoms, and have linked this to carbon dioxide limitation within sea-ice assemblages. Enrichment of ^{13}C in sediments has been suggested as a proxy for past carbon dioxide concentrations in surface waters (Rau et al. 1989, 1991a). However, laboratory investigations by Gleitz et al. (1996), and field investigations (Dunbar and Leventer 1992; Gibson et al. 1999) have shown that ^{13}C enriched carbon of sea-ice diatoms may confound any reconstruction of past surface carbon dioxide concentrations in seasonally ice-covered regions.

In some Antarctic coastal regions, fast ice persists well into the summer. This ice can often support high algal standing stocks with extremely productive bottom ice assemblages (McMinn et al. 1999). However, often an additional layer of accumulated platelet ice under the fast-ice cover enhances the biological activity. These layers form a semi-enclosed system with, at times, restricted exchange with the underlying water column (Dieckmann et al. 1992; Arrigo et al. 1995; Günther and Dieckmann 1999; Günther et al. 1999a). Although light and inorganic nutrient limitation are known to occur within platelet-ice systems, these habitats are well known as supporting the highest algal biomass ever measured in sea ice (1 mg Chl*a* l^{-1}, Arrigo et al. 1995). At the Drescher Inlet in the Riiser Larssen ice shelf, Günther et al. (1999b) investigated the biogeochemical processes taking place during growth and accumulation of algal biomass within platelet ice. As well as showing that inorganic nutrients become limiting and that there are shifts in the carbon metabolism of the diatoms, Günther et al. (1999a) also showed the platelet layer to be a rich grazing ground for a wide range of metazoans dominated by small copepods and amphipods.

The objective of the present study was to measure the export and the nature of particulate organic matter sedimenting from the platelet layer in Drescher Inlet, and asses the flux to the underlying sediments. The measurements were made in late summer, when the maximum flux from the platelet layer would be predicted. Another objective of the study was to compare the composition and chemistry of the particle flux with that in the platelet layer and water column. An array of sediment traps was deployed under a platelet-ice layer within the inlet and a suite of biogeochemical parameters within the platelet ice and water column measured concurrently. The campaign was curtailed by premature break up of ice within the inlet, although these unforeseeable events did offer the opportunity to study the effect of intensive ice break-up on particle flux. A focus of the study was the stable carbon isotope composition of the sedimenting organic material as a tracer for ice algae. These measurements, together with other parameters, would help in the clarification of bentho-pelagic coupling and the role of sea-ice systems in this coupling.

Materials and methods

Study site

The study was conducted during a 5-week field campaign at the Drescher Inlet in austral summer 1998 (Dieckmann and Thomas 1999). The inlet, a 20-km-long funnel-shaped crack in the Riiser-Larsen ice shelf (72°52′S, 19°25′W) in the eastern Weddell Sea (Fig. 1), is flanked by floating ice cliffs approximately 30 m above and 150 m below the sea surface. The inlet has an irregular topography with water depths varying between 360 and 400 m (Plötz and Bornemann 1999). The inlet is characterised by a stable fast-ice cover lasting throughout the summer and an underlying platelet-ice layer, which can reach thicknesses of >20 m. From 7 to 13 February, the weather was good and the sea-ice cover in the inlet, stable. From 14 to 23 February, weather conditions deteriorated, and there was intensive ice break-up, with three-quarters of the inlet being ice-free by the end of the field campaign.

Although the ice at the mouth of the inlet was 1 year old ice no more than 2 m thick, towards the back of the inlet the ice was multi-year ice of 6 m or greater thickness. At the study site (Fig. 1), the sea ice was approximately 4 m thick with a highly variable snow cover ranging from 0 to 2 m thick. There was no evidence of significant biological activity within the overlying sea ice.

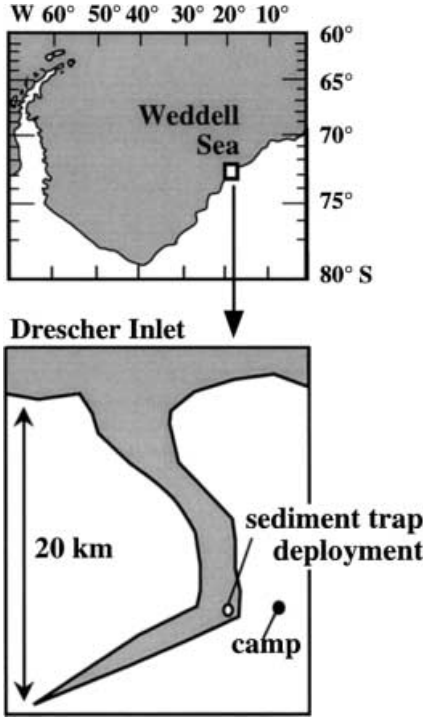

Fig. 1 Location of the Drescher Inlet in the Riiser-Larson Ice Shelf, eastern Weddell Sea. In the *lower panel* the inlet and the sediment trap array deployment site are shown

Sampling

Water column and platelet-ice layer

On three occasions, discrete water samples were collected at 50, 150 and 400 m under the ice, and on one occasion from the ice edge using a 5-l Niskin bottle. Twelve CTD profiles down to 400 m were measured using a newly calibrated Seabird SBE 19 CTD profiler. The Niskin bottle and CTD casts were deployed with a modified Valeport electric winch.

The platelet ice was sampled using an Adonis-type sampler (Dieckmann et al. 1992; Günther and Dieckmann 1999). The device allows the high-resolution discrete sampling of interstitial water from between the ice platelets. Recent tests by Günther et al. (1999b) have shown this system to be suitable for the collection of samples for dissolved gas analyses, as well as biological composition and inorganic nutrient chemistry.

The interstitial platelet water and water column samples were filtered in the field laboratory through precombusted GF/F filters (Whatmann, 450°C, 3 h). Samples for Chlorophyll *a* (Chl*a*), particulate organic carbon, nitrogen, phosphorus (POC/PON/POP) concentrations and stable carbon isotope composition of POC ($\delta^{13}C_{POC}$) were collected on filters and stored frozen until analysis in the home laboratories. Filtrates were poisoned with $HgCl_2$ and stored at 4°C in 50-ml PE bottles for later inorganic nutrient and dissolved organic nitrogen (DON) analyses (Kattner 1999). Additional filtrate samples were stored frozen (unpoisoned) in 50-ml precombusted (450°C, 3 h) glass ampoules for later dissolved organic carbon (DOC) determination.

Sub-samples for oxygen concentration, pH and alkalinity were taken immediately after retrieval, avoiding atmospheric contamination (Gleitz et al. 1995; Günther et al. 1999b). Additional samples were collected for the carbon isotopic composition of dissolved inorganic carbon ($\delta^{13}C_{DIC}$). They were immediately filtered through in-line 0.45-µm polycarbonate filters avoiding contamination with air bubbles. The filtrates were poisoned with $HgCl_2$ and sealed under an atmosphere of nitrogen in pre-weighed glass ampoules.

From each sample, 100-ml aliquots were preserved with hexamine-buffered formaldehyde (final concentration ca. 0.5%) for microscopic examination.

Sediment trap deployment

An array of four sediment traps and an Aanderaa RCM 8 current meter (Fig. 2) were deployed (by hand) on 2 February. The array was anchored to the overlying sea ice and deployed through a large crack in the ice. Two types of Hydrobios cylindrical sediment traps were deployed, both with opening areas of 0.015 m^2. The trap openings were covered by a plastic grid 40 mm thick, with 40 mm^2 holes. The trap-collecting cylinders were 560 mm long.

The "multiple" traps (Hydrobios-MST 6) had six collecting bottles, each programmed to collect samples over 6 days. The "single" traps were equipped with only one collecting bottle. Prior to deployment, all collecting cups were filled with slightly hypersaline water and poisoned with $HgCl_2$.

Multiple traps were positioned at 10 m, just below the platelet layer, and at 360 m close to the seafloor (approximately 400 m). Single-bottle traps were placed above (115 m) and below (230 m) a sharp thermocline determined by a CTD profile. However, it should be noted that the by the end the thermocline extended down to 280 m (see Fig. 4 and later discussion on hydrography). The array was deployed for 15 days, and had to be recovered due to the impending break-up of the ice in the inlet. The upper multiple trap worked as programmed, giving samples of 6, 6 and 3 days collection. However, the bottom multiple trap yielded only two samples of 6 and 9 days collection. After recovery of the traps, samples from the trap cups were split in the field laboratory and sub-samples taken for POC/PON, Chl*a* and $\delta^{13}C_{POC}$ determinations and for microscopic examination as described above.

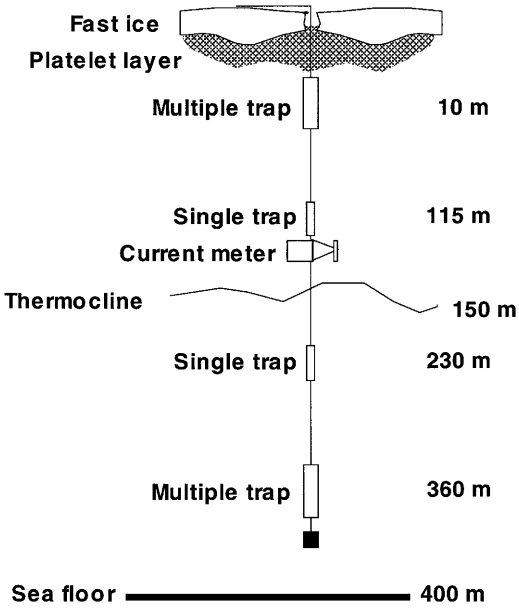

Fig. 2 Sediment trap and current meter array deployed on 2 February 1998 at Drescher Inlet under a fast-ice cover with a well-developed underlying platelet layer. The position of the thermocline was determined by CTD profiles (see Fig. 4). "Multiple" traps had multiple collecting bottles whereas "Single" traps were equipped with single sampling bottle

Analytical methods employed

In the field laboratory

Oxygen concentrations were determined using the Winkler method (Grasshoff 1983). The pH and total alkalinity were measured as described by Gleitz et al. (1995) and Günther et al. (1999b). The carbonate system was calculated from pH and alkalinity using the carbonic acid dissociation constants of Mehrbach et al. (1973). Concentrations of dissolved carbon dioxide and pH of the platelet interstitial water were calculated for a temperature of 0°C, and for the water column samples, for the in situ temperature determined from the CTD casts. Salinity was measured at laboratory temperature using a WTW microprocessor conductivity meter.

In Bremerhaven and Bangor

Chlorophyll *a* was determined using a Turner fluorometer, after overnight extraction in 90% acetone in the dark at 4°C (Evans et al. 1987). Inorganic nutrient analyses (nitrate, nitrite, silicate, ammonium, phosphate) were performed using standard autoanalyser methods (Kattner and Becker 1991). DON was analysed following persulphate wet oxidation (Kattner and Becker 1991), and DOC by high temperature oxidation using an MQ1001 TOC Analyser (Qian and Mopper 1996).

Filters for POC and $\delta^{13}C_{POC}$ were acid fumed (concentrated HCl) overnight to remove carbonate, dried at 40°C and then stored in a desiccator prior to analysis. POC and PON concentrations were determined with a Europa Scientific CHN analyser, using acetanilide as a standard. POP was measured essentially after Kattner and Brockmann (1980). Samples for $\delta^{13}C_{POC}$ analyses were processed, and subsequently analysed using a VG SIRA II isotope ratio mass spectrometer as described by Kennedy and Robertson (1995). Samples for $\delta^{13}C_{DIC}$ were processed as described by McCorkle (1987). The carbon isotope ratios are expressed in the standard $\delta^{13}C$ (‰) notation relative to the Pee Dee Belemite, with a precision (including sample collection and extraction) of ± 0.07‰.

The formaldehyde-fixed samples were examined by a combination of light and electron microscopy techniques. To facilitate the examination, fractions of different densities were taken following a range of settling periods up to 24 h. The major component of the material in the sediment traps was faecal pellets, which were classified by size using calibrated graticules in inverted microscopes.

Results

Hydrography

The automatic weather station, ARGOS (maintained by the Alfred Wegener Institute), at the camp location at Drescher (Fig. 1) recorded significant changes in the weather during the deployment period (Fig. 3): between 2 and 12 February the mean wind speed was 2.28 m s^{-1} (max. 5.43 m s^{-1}), increasing from 13 to 18 February up to 4.88 m s^{-1} (max. 11.75 m s^{-1}). Water currents at 120 m during the same period were mainly orientated to the south, with a mean speed of approximately 2 cm s^{-1}. A northeastward-directed water current was preceded by the maximum wind speed recorded on 14 February. The current peaked 2 days later with maximum velocities of 6 cm s^{-1} (Fig. 3). The high wind speed coupled with high water current speeds were followed by the massive sea-ice break-up within the inlet that was most intensive on 17 February, when the deployment was obviously ended.

These changes in wind and water current speed were also reflected by changes in the hydrography of the inlet (Fig. 4). The temperature and salinity profiles in the inlet were characterised by a stable sharp thermo- and pycnocline between 150 and 180 m water depth. On 3 February, near the beginning of the sediment trap deployment, the surface waters were also cooled down, forming a distinct shallow thermocline and pycnocline at 30 m. The lower temperature and reduced salinity in the first 30 m are clearly influenced by the platelet layer, which was observed to extend down to 25 m in places in the inlet.

During the ice break-up, warm deep water was entrained due to surface water export caused by high wind speeds and the northeastward-directed current on 16 February (Fig. 3). This resulted in a warming up of the upper water column (Fig. 4), which will have promoted platelet and sea-ice melt. The thermo- and pycnoclines also became more diffuse, extending from 150 to 280 m water depth (Fig. 4).

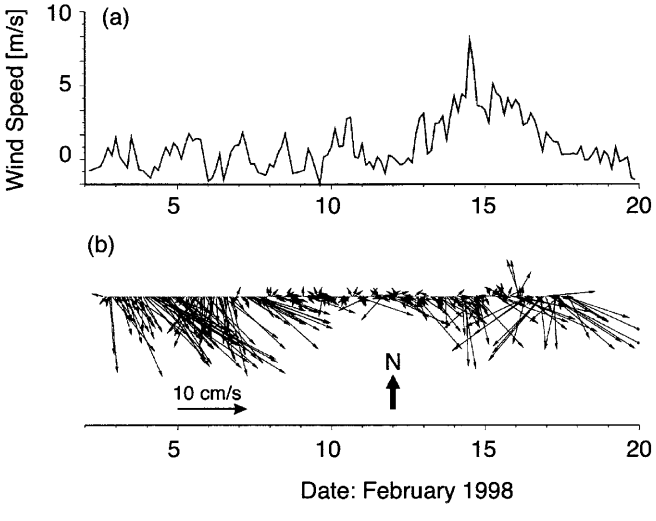

Fig. 3 Wind speed (**a**) and water current meter data (**b**) collected during the 15-day sediment trap deployment. The water current vectors indicate direction and current velocity on a 60-min integrated scale. The wind speed data were collected by the automatic weather station ARGOS at the Drescher camp (see Fig. 1 for location)

Platelet ice and water column

There were obvious differences in the biology and chemistry of the platelet layer compared with the underlying water column (Table 1). It should be noted that just taking interstitial water samples from the platelet layer underestimates the biomass of ice algae living within this layer. Grossmann et al. (1996) showed that the larger percentage of *Fragilariopsis*-dominated assemblages were attached to the ice platelets rather than in the interstitial water. Similarly, Dieckmann et al. (1992) reported that ca. 47% of the Chl*a* in the platelet ice is associated with the platelet ice crystals. During this campaign, a similar comparison was made on two occasions. When the concentration of POC was compared, the interstitial water levels were 20 and 24% of that on the surrounding platelets. However, it is not unreasonable to compare chemical characteristics of the platelet interstitial waters with the underlying water, since the chemistry of the interstitial water is a reflection of the biological activity of both components of the platelet layer, and not simply the interstitial assemblage.

Although other species were present, the platelet-layer assemblages were dominated by *Fragilariopsis* species, predominantly *F. cylindrus* and *F. curta*. Comparing mean values, there was 7 times more Chl*a* in the platelet interstitial water compared with the water column, although this enrichment was only 4 times for POC and PON. There was significantly greater enrichment of POP in the platelet interstitial water, mean concentrations being 12 times higher than those in the underlying water (Table 1). This differential chemical enrichment led to very different elemental ratios between the organic matter in the platelet interstitial water and the water column. The mean POC:PON ratios of the particulate phases were similar in both platelet interstitial water and the underlying water column, although the lower end of the range for the interstitial water was lower than that measured in the water column samples. Both the POC:POP and PON:POP ratios were lower in the interstitial water than in the water column. Although there was considerable variation in the data, the PON:POP and POC:POP ratios in the water column had mean values closer to Redfield values of 106:1 and 16:1,

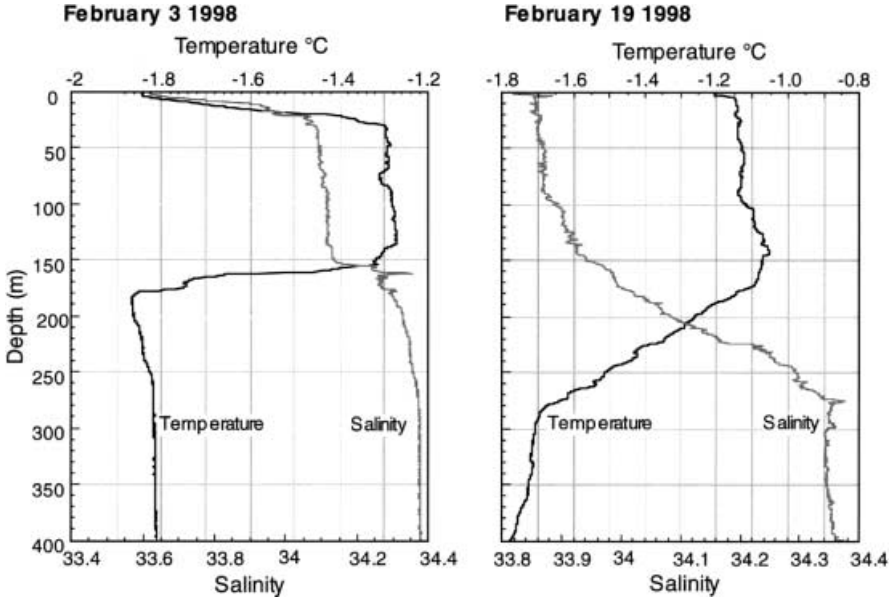

Fig. 4 Temperature and salinity profiles from CTD casts at Drescher Inlet on 3 and 19 February 1998, corresponding to the beginning and end of the sediment trap deployment

respectively, compared with those from the platelet interstitial water.

Differences in biomass were reflected in the inorganic nutrients within the two systems (Table 1). The concentrations of nitrate and silicate were significantly lower in the platelet interstitial water, and ammonium levels considerably elevated. Although the mean phosphate concentrations were not significantly different, the minimum levels recorded were very much less in the platelet interstitial water than in the underlying water. Nitrite concentrations were similar in both interstitial water and the water column. The concentrations of inorganic nutrients of the underlying water are typical of Weddell Sea water (Schröder et al. 1994). Concentrations of DOC and DON were twice as high, with a lower DOC:DON ratio, in the platelet interstitial water compared with those measured in the underlying water column (Table 1).

Table 1 Summary of chemical and biological parameters measured in interstitial water of the platelet-ice layer and the underlying water column. Mean values are given and the range of values (minimum-maximum) are given *in parentheses*. Samples were taken between 0.2 and 1.8 m in the platelet layer, and at 50, 150 and 400 m in the water column (*DIC* dissolved inorganic carbon, *Chla* chlorophyll, *POC*/*PON*/*POP* particulate organic carbon/nitrogen/phosphorus, *DOC*/*DON* dissolved organc carbon/nitrogen, $\delta^{13}C_{DIC}$ carbon isotopic composition of DIC, $\delta^{13}C_{POC}$ carbon isotopic composition of POC)

Parameter	Platelet interstitial water	Water column	Number of measurements	
			Platelet layer	Water column
Salinity	33.0 (31.1–33.9)	34.1 (33.9–34.4)	13	8
pH	8.46 (8.25–8.90)	8.23 (8.13–8.29)	10	8
DIC (μM)	2064 (1723–2199)	2258 (2227–2346)	10	8
CO_2 (aq) (μM)	12.3 (2.9–18.3)	20.1 (17.1–25.9)	10	8
O_2 (μM)	385.5 (325.5–514.0)	330.5 (253.6–373.9)	14	8
Chl*a* (μg/l)	3.0 (0.1–9.9)	0.4 (0.0–1.7)	13	8
POC (μM)	47.1 (8.8–155.1)	12.0 (5.7–19.3)	13	8
PON (μM)	5.5 (0.7–19.8)	1.26 (0.5–1.9)	13	7
POP (μM)	1.1 (0.1–4.0)	0.08 (0.0–0.2)	7	7
POC:PON	9.8 (6.2–12.2)	9.5 (7.1–12.1)	13	7
PON:POP	8.4 (4.2–13.6)	13.7 (8.0–22.0)	7	6
POC:POP	75.9 (39.1–96.0)	123.8 (75.7–189.7)	7	6
POC:PON:POP	106:12:2.4	106:11:0.8		
$\delta^{13}C_{POC}$ (‰)	–24.0 (–20.9 to –26.7)	–25.6 (–24.6 to –26.3)	11	8
$\delta^{13}C_{DIC}$ (‰)	1.4 (0.4–3.8)	0.7 (0.1–1.2)	13	7
Nitrate (μM)	15.7 (0.4–24.3)	25.4 (21.3–32.7)	13	7
Nitrite (μM)	0.1 (0.0–0.2)	0.1 (0.07–0.1)	13	7
Ammonium (μM)	4.2 (1.2–9.0)	1.4 (0.93–1.8)	13	7
Silicate (μM)	40.3 (4.1–62.2)	65.2 (59.48–71.1)	13	7
Phosphate (μM)	1.17 (0.2–1.8)	1.3 (1.04–1.4)	13	7
DOC (μM)	146.8 (100.8–200.6)	72.4 (55.4–85.6)	12	7
DON (μM)	24.5 (8.8–56.3)	3.7 (2.0–5.2)	12	6
DOC:DON	8.2 (2.3–20.5)	21.4 (15.3–27.1)	11	5

Elevated oxygen concentrations were measured in the platelet interstitial water, which were linked to lower concentrations of dissolved inorganic carbon (DIC) and CO_2 (aq). Likewise, elevated pH values were measured in the platelet interstitial layer, typical of ice environments with active algal assemblages with somewhat restricted water exchange. The decrease in DIC concentration was reflected in the more positive carbon isotope values of $\delta^{13}C_{DIC}$ compared with those typically found in seawater. This enrichment of ^{13}C in DIC samples is also reflected in a corresponding enrichment in the $\delta^{13}C_{POC}$ values in platelet interstitial assemblages (Table 1).

Particle flux

It is striking that the highest faecal pellet, Chl*a* and phaeopigment fluxes were at 230 m just below the thermocline (Table 2). The POC flux was only slightly higher below the thermocline than above, which was opposite to that for PON. In contrast, the POP flux was clearly higher above the thermocline (Table 2). The POC:PON ratios had a small range in values, although there was a difference between samples collected either side of the thermocline. Above the thermocline, the mean for all samples was 6.6, close to the Redfield ratio for fresh phytoplankton material, whereas in the samples collected below it was somewhat higher at 7.4. POC:POP and PON:POP ratios were more variable, but still showed lower ratios (i.e. high phosphorus content) above the thermocline.

There was little trend in the $\delta^{13}C_{POC}$ values with depth of sediment trap. The values above the thermocline were more variable ($\delta^{13}C_{POC}$ –25. 5, SD = 0.07, $n = 4$) than below ($\delta^{13}C_{POC}$ –26.6, SD = 0.4, $n = 3$), but not significantly different. In the samples where the flux of faecal pellets was less than 1×10^5 pellets m^{-2} day^{-1}, the $\delta^{13}C_{POC}$ values were more negative than –26‰ (first 6 days at 10 m and both sampling periods at 360 m), whereas at greater faecal pellet flux they were more positive than –26‰ (Table 2).

Comparing the pigment concentrations, it is pertinent to consider a pigment degradation ratio derived by dividing the phaeopigment flux by the sum of the chlorophyll plus phaeopigment flux (Table 2). There was significant degradation of chlorophyll in material in the top three traps (degradation ratios of 70–79). Since in the 10-m trap the ratios varied from 70 to 79, no trend of increasing pigment degradation with depth was recognisable down to 230 m. At 360 m, the pigment degradation ratios did increase to between 87 and 91, indicating that there was increased pigment degradation in the deepest trap compared with those above (Table 2).

The sediment trap samples were dominated by faecal pellets (Fig. 5). The contents of the pellets, independent of pellet size, were mostly diatom frustules almost exclusively from the genus *Fragilariopsis*, and mostly

Table 2 Summary of biochemical parameters measured on sediment trap material collected on a 15-day deployment of traps at 10 m, 115, 230 and 360 m under a platelet-ice layer/fast-ice cover at Drescher Inlet in February 1998. The traps at 10 m and 360 m collected multiple samples during the deployment, whereas the traps at 115 and 230 m collected over the whole 15 days (*Chla* chlorophyll, *POC*/*PON*/*POP* particulate organic carbon/nitrogen/phosphorus, $\delta^{13}C_{POC}$ carbon isotopic composition of POC)

Depth of trap	Number of days collected	Chl*a* ($\mu g\ m^{-2}\ day^{-1}$)	Phaeopigments ($\mu g\ m^{-2}\ day^{-1}$)	Pigment degradation ratio[a]	POC ($mmol\ m^{-2}\ day^{-1}$)	PON ($mmol\ m^{-2}\ day^{-1}$)	POP ($mmol\ m^{-2}\ day^{-1}$)	POC:PON	POC: PON:POP	$\delta^{13}C_{POC}$ (‰)	Faecal pellets ($nos.\ m^{-2}\ day^{-1}$)
10 m	6	37.5	112.4	75	4.75	0.62	0.11	7.6	106:14:2.5	–26.5	0.4×10^5
	6	37.0	143.6	79	5.47	0.85	0.06	6.5	106:16:1.2	–25.4	1.3×10^5
	3	73.1	170.4	70	5.77	0.90	0.13	6.4	106:16:2.4	–25.0	3.1×10^5
115 m	15	112.6	364.6	76	8.71	1.49	0.11	5.8	106:18:1.3	–25.2	5.7×10^5
230 m	15	261.7	997.1	79	9.29	1.31	0.05	7.1	106:15:0.6	–25.8	14.0×10^5
360 m	6	76.5	509.3	87	4.12	0.51	0.02	8.0	106:13:0.5	–26.6	0.8×10^5
	9	77.5	745.6	91	3.65	0.51	0.02	7.2	106:15:0.6	–26.2	0.9×10^5

[a] Pigment degradation ratio = phaeopigments/(phaeopigments + Chl*a*)

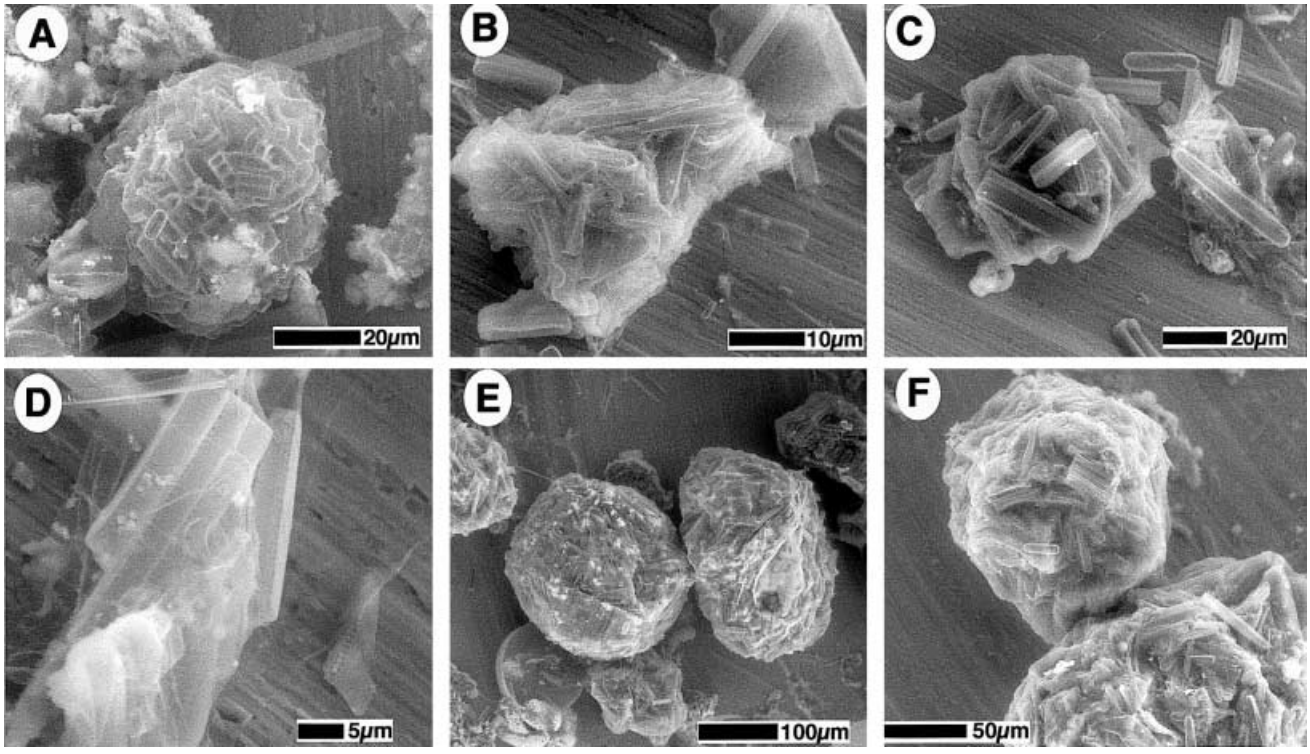

Fig. 5 Scanning electron micrographs of faecal pellets collected in sediment traps at 112 m (**A**), 122 m (**E**) and 230 m (**B**, **C**, **D**, **F**) depth. Note the difference in scale bars for each micrograph

F. cylindrus and *F. curta*. It was striking that these diatoms were largely intact and often in chains several cells long. The faecal pellets were of either undefined shape or very compact spherical pellets. No oval/elipsoid-shaped or krill pellets were seen in any of the samples. The pellets were size-classed, and in all trap samples 50% of the pellets were less than 97 μm in diameter (Fig. 6). The bottom trap had the greatest proportion of large pellets, and up to 20% of the pellets were greater than 244 μm in diameter. Although their origin is not certain, it is thought that they are probably produced by amphipods (U. Bathmann, personal communication). Amphipods were collected in traps at all depths, as were calanoid and cyclopoid copepods. An unidentified polychaete was found in both the 10-m and 115-m traps, and an unidentified salp at 115 m (metazoans were removed before samples were filtered for chemical analyses). The smaller pellets (up to 97 μm in diameter) are thought to be

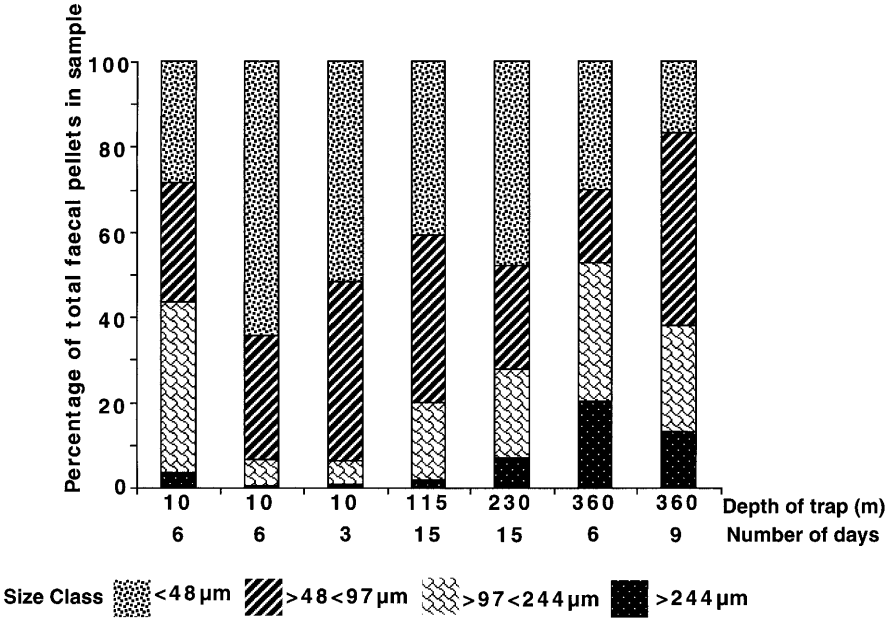

Fig. 6 Size distribution of faecal pellets collected at 10 m, 115 m, 230 m and 360 m at Drescher Inlet. The *key* gives the size classes measured. At 10 m and 360 m multiple collections were made, whereas at 115 and 200 m only single collections were made over the 15-day deployment period

predominantly produced by protozoans (U. Bathmann, personal communication). Although the faecal pellets from the 10-m, 115-m and 230-m traps' collections were uniformly intact, it was noticeable that the pellets from 360-m were more fragmented. There was little evidence of bacteria on the surfaces of any of the pellets or debris in the traps. Sponge spicules were noted in the 360-m and, to much less extent, the 200-m trap samples. This is evidence that there may have been a degree of resuspension from the benthos.

Temporal trends in flux rates were discernable in the sediment trap deployed at 10 m. There was an increasing flux of faecal pellets, Chl*a*, phaeopigments, POC and PON, although not of POP (Table 2). This trend is most likely due to the increasing wind and surface water current velocities and the gradual increase in ice breakup in the inlet. The nature of the flux also changed with increasing $\delta^{13}C_{POC}$ values. The daily flux of faecal pellets, Chl*a*, POC, PON and POP in the 360-m trap did not change significantly with time, and there were no temporal changes in $\delta^{13}C_{POC}$. The pigment degradation ratios indicate no evidence of change with time in the degree of pigment degradation in either the 10-m or 360-m trap.

A comparison between the nature of the material collected in the traps with that found in the platelet interstial water and underlying water column showed considerable differences. The POC:PON ratios measured in the sediment trap material were lower (mean 6.1, Table 2) compared with the mean ratios of the platelet interstitial water and water column (9.8 and 9.5, respectively, Table 1). Only in a few samples from the platelet layer were the POC:PON ratios similar to those in the sediment traps. The variability in the POP measured in the ice and water column makes it impossible to compare the data with those obtained in the sediment traps. No evidence of ^{13}C enrichment in the $\delta^{13}C_{POC}$ in the sediment trap material was measured. The range of $\delta^{13}C_{POC}$ values in the sediment trap material (Table 2) is within the ranges measured for the platelet interstitial water and water column, although within the platelet ice, more ^{13}C-enriched material ($^{13}C_{POC} = -20.9‰$) was present.

Discussion

The magnitude of the daily POC flux during this study is not exceptional, and is within the ranges of fluxes recorded at other ice-covered sites for the same time of year: Ross Sea (Dunbar et al. 1998; Smith and Dunbar 1998; Asper and Smith 1999), McMurdo Sound (Dunbar and Leventer 1986), Kapp Norvegia (Bathmann et al. 1991), Lutzow-Holm Bay (Matsuda et al. 1987), Terra Nova Bay (Pusceddu et al. 1999) and Halley Bay (González et al. 1994). As in the present study diatoms, and in particular ice algae, were found in all of these studies to be the principal contributors to the organic flux collected by the sediment traps.

A flux of ice diatoms from an overlying ice cover to the sediment is well recorded in previous sediment trap studies carried out in ice-covered regions of the Southern Ocean (Leventer and Dunbar 1987; Fischer et al. 1988; Dunbar et al. 1998). The major diatoms in the traps were *F. curta* and *F. cylindrus*, two species consistently identified as dominating sea-ice assemblages and marginal ice-edge zones. The dominance of these two species has led to their use as sea-ice proxies in palaeoenvironmental studies (see review by Leventer 1998). Although both species were present in the water column, the biomass was so low that it is reasonable to conclude that the source of this algal flux was from the platelet layer underlying the fast ice in the inlet, mediated by a packaging in the form of faecal pellets. A similar highly significant contribution of faecal pellets to summer particle flux was recorded by Dunbar et al. (1998), who noted pellets being primarily composed of unfragmented diatom frustules, mainly *F. curta*.

One of the most striking observations about the faecal pellets was the integrity of the frustules. Only on a very few occasions were broken frustules observed, and apparently the diatoms are effectively transported to the benthos intact. Smetacek (1999a, b) discussed how heavy silicification of diatom frustules enhances their transfer to depth, and hence why diatoms dominate the biological pump. In his discussion he also points to how protists, in particular dinoflagellates, are voracious grazers on the diatoms, maybe even more so than the larger metazoans such as copepods and krill. The producers of the faecal pellets collected in this study cannot be determined, although we speculate that the majority of the pellets up to 97 μm were produced by protozooplankton such as heterotrophic dinoflagellates, ciliates, foraminiferans and radiolarians (Nöthig and von Bodungen 1989; González 1992). These accounted for over 50% of the trap material, and in the traps at 10, 115 and 230 m, up to 90% of the faecal pellets present. Spindler and Dieckmann (1986) reported high numbers of foraminiferans in sea ice from Drescher Inlet, and there are various reports of high levels of small copepods living in the platelet ice in the inlet (Schnack-Schiel et al. 1995; Günther et al. 1999a). The rest of the faecal material is again of unknown origin, but will have been produced by metazoan grazers, the largest pellets being produced most probably by amphipods. No krill faeces were found, which contrasts with many other sites in the Southern Ocean where such material has represented the major component of sediment trap collections (see citations in Nöthig and von Bodungen 1989).

One of the characteristics of the present study was that the traps were deployed under thick multi-year fast ice, with little evidence of ice algal activity within the ice itself. The only algal growth that was taking place at this site was within the underlying platelet ice layer. Even within the platelet layer, the algal standing stock was low compared with other late summer studies conducted at other coastal fast-ice sites (Dieckmann et al. 1992; Arrigo et al. 1993; Günther and Dieckmann 1999;

Günther et al. 1999b). This is a reflection of the thick fast ice overlying a thick platelet ice layer that had probably accumulated over many more months than is usual at other sites. The resulting low irradiance limits the growth of diatoms considerably. In spite of this, the standing stock of diatoms in the interstitial water was almost an order of magnitude higher than that measured in the underlying water column.

Diatom growth in the platelet layer, whether in the interstitial water or attached to platelets, resulted at times in depletion of inorganic nutrients and, in the case of nitrate, phosphate and silicate, almost to exhaustion. In contrast, as described in several other studies (Dieckmann et al. 1991; Thomas et al. 1998; Guglielmo et al. 2000), ammonium levels in the platelet layer were high, as were levels of dissolved organic carbon and nitrogen (DOC 146 μM, DON 25 μM). These levels of dissolved organic matter are twice as high as those reported for Antarctic surface waters (Kähler et al. 1997; Wedborg et al. 1998), which together with the high ammonium levels are indicative that remineralisation processes are high (Dieckmann et al. 1992; Arrigo et al. 1995; Günther and Dieckmann 1999). The ratio of DOC:DON indicates significant enrichment of nitrogen (cf. Thomas et al. 1995) compared with values in the open-water samples, which were typical for open-water ratios (Williams and Druffel 1988). In fact, the values of DOC:DON are of a similar magnitude to that of POC:PON in the platelet interstitial water, whereas in the water column the ratios of the dissolved phase are double that of the particulate phase. These measurements confirm the hypothesis that concentrations of dissolved organic matter are high within platelet ice systems (Grossmann et al. 1996; Günther et al. 1999b), although not as high as in other sea-ice habitats (Thomas et al. 1998).

The elemental composition of diatoms is governed by many factors, although primarily by inorganic nutrient (including inorganic carbon) supply (Burkhardt and Riebesell 1997 and citations therein). Phosphorus in the particulate material of the platelet layer was enriched compared to carbon using the Redfield ratio as benchmark. This enrichment in phosphorus was also measured in the trap material above the thermocline. In contrast, phosphorus was depleted in the particulate material in the water column and considerably so in the contents of the two deep trap samples. In both the platelet interstitial water and water column, there was evidence that the nitrogen content of the particulate material was depleted. There was no evidence of this depletion in the trap samples above the thermocline, although material collected below the thermocline did show slight nitrogen depletion compared with carbon. Phosphorus is already remineralised to ortho-phosphate to a considerable extent above the thermocline, and the trap samples clearly indicate that material reaching the sediment is poor in phosphorus and slightly reduced in nitrogen compared to carbon.

Increased biological activity within the platelet-ice layer led to the higher pH, lower dissolved inorganic carbon and CO_2 (aq) and elevated oxygen concentrations within the interstitial water. Similar magnitudes of oxygen enrichment and DIC depletion were found in platelet layers by Günther et al. (1999b) and in sea-ice brines by Gleitz et al. (1995). The decrease in DIC was also reflected in the more positive carbon isotope values of $\delta^{13}C_{DIC}$, which result from the production of isotopically depleted organic carbon during photosynthesis (Smith and Kroopnick 1981). The ^{13}C enrichment in DIC is also reflected in a corresponding enrichment in the $\delta^{13}C_{POC}$ values in platelet-ice assemblages. Enriched ^{13}C in $\delta^{13}C_{POC}$ values up to –11‰ have been reported by McMinn et al. (1999), and values of –8‰ in sea-ice cores by Dunbar and Leventer (1992). Fischer (1991) and Rau et al. (1991b) measured enrichment of ^{13}C in $\delta^{13}C_{POC}$ collected from ice cores and it has been concluded that this results from the ice restricting gas exchange, in combination with high rates of algal growth resulting in the enrichment of ^{13}C in the remaining DIC. Highest biomass of algae in the sea ice results in the most ^{13}C-enriched values and they are assumed to be due to the limited CO_2 exchange with the external seawater.

Oxygen enrichment and DIC depletion in sea-ice brines obtained by sack-hole sampling (Gleitz et al. 1995) confirm that sea-ice algal communities modify the brine chemistry. These field measurements were extended to the laboratory, where Gleitz et al. (1996) compared diatom growth, enrichment in $PO^{13}C$ with changing DIC, and pH and oxygen trends in sea ice, simulating closed incubations. To our knowledge, the measurements in the study reported here are the first of $\delta^{13}C_{DIC}$ to be made in any sea-ice system and confirm the results that enrichment in $\delta^{13}C_{POC}$ takes place within the semi-enclosed ice matrix.

If POC enriched in ^{13}C is being produced in sea ice, it is reasonable to predict that material sinking out from sea ice may result in ^{13}C-enriched sediments, irrespective of regional surface water variations in the partial pressure of carbon dioxide (Dunbar and Leventer 1992). Wada et al. (1987) concluded that high values of –20‰ originated from deposition of ice algae grown under CO_2-limited conditions.

One of the major aims of this present study was to trace the source of the organic matter to the underlying sediments and link enrichment of ^{13}C in the organic matter produced in the platelet ice with that in sedimenting material from the ice. Stable isotopes are commonly used to trace organic matter sources and to elucidate the degree to which benthic consumers are coupled to pelagic primary production (Hobson et al. 1995). Gibson et al. (1999), working at a near-shore site in Prydz Bay, measured pronounced seasonal variation in carbon isotopes. Winter values were nearly constant around –20‰, increasing to above –15‰ after inputs of sea-ice algae in spring. The platelet-ice system, however, does not form such an isolated habitat as sea-ice sheets. Yet, as already stated, platelet-ice layers are systems where rates of exchange and replenishment of dissolved inorganic nutrients and gases may be restricted. The

data from the interstitial waters of the platelet layer above the traps confirm that this was the case during the time of sampling. However, in the sediment traps there was no evidence of this material being transported to depth as there were no significant differences in the chemistry of trap material compared with that from the water column. In fact, most positive $\delta^{13}C$ values for the open-water samples are higher than in any sample collected in the traps.

One possible explanation for this apparent discrepancy is that the algae that were being grazed and sinking from the platelet ice were those that were on the outer edges of the platelet layer, and hence located in regions where exchange with surrounding seawater was possible. This explanation is also supported by the elemental composition of the sediment trap material, which does not have the elevated POC:PON ratios measured within the platelet layer, but rather a ratio more akin to diatoms growing in inorganic nutrient-replete conditions.

The short field campaign in which this study took place by default results in our obtaining only a brief "snap-shot" of the nature and flux of the organic matter from the platelet layer to the underlying benthos. The effects of carbon limitation of the stable carbon isotope signature of ice algae, and the subsequent incorporation into sediments is clearly not as straightforward as has been reported elsewhere. Before the use of ^{13}C-enriched sediments as a proxy for sea-ice cover can be employed, more extensive seasonal studies must be conducted, and more rigorous attention paid to collecting efficiency and characterising the biogeochemical processes taking place in sea ice and platelet layers. However, the results have raised important questions that need to be addressed if we are to understand the importance of sea-ice primary production and the benthic-pelagic coupling in Antarctic waters and, in particular, for shallow coastal regions such as the Drescher Inlet.

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