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Sediment characteristics at selected sites of the Ross Sea continental shelf: does the sedimentary record reflect water column fluxes?

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Abstract: Flux data from moored sediment trap experiments and mass accumulation rates in sediments were obtained for three sites in the Ross Sea which are currently studied for the formation and transit of High Salinity Shelf Water and Ice Shelf Water. These two data sets were compared to obtain inferences on the coupling between water column processes and sedimentary records. The depth distribution of physical features and concentrations of organic carbon and biogenic silica in box cores and gravity cores were studied. Mass accumulation rates, established on the basis of two conventional ^{14}C dates for each core, range between 7.64 and 19.46 g m^{-2} yr^{-1}. Although these are productive areas, downward fluxes measured by sediment traps are low: 7.5–25.6, 2.4–17.9 and 0.5–0.9 g m^{-2} yr^{-1} for particles, biogenic silica and organic carbon, respectively. The concentrations of biogenic components in surficial sediments are correspondingly low. Simple mass balances were calculated assuming the conservative behaviour of the lithic fraction of sinking materials and sediment. Lateral advection of suspended particles is needed to balance the fluxes at the three sites. Furthermore, the model suggests that the preservation of biogenic components is lower than at other sites of the Ross Sea, probably due to the low accumulation rates that imply a high residence time of biogenic materials at the sediment-water interface.

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Introduction

High-latitude environments experience frequent algal blooms during the spring–early summer retreat of the seasonal sea ice cover. These can generate high pulses of biogenic particulate export from surface waters, especially when algal assemblages are composed of diatoms. Furthermore, satellite observations showed that each year the Ross Sea exhibits the most spatially extensive biomass in the Southern Ocean (Comiso *et al.* 1993, Sullivan *et al.* 1993, Arrigo *et al.* 1998). Recently, Smith & Gordon (1997) and Smith *et al.* (2000) were able to confirm the hyperproductive nature of the Ross Sea through a series of spring process studies in its southern portion. Due to the high preservation potential, the Ross Sea continental shelf is an area of high accumulation of biogenic silica in the sediments (Ledford-Hoffman *et al.* 1986, DeMaster *et al.* 1996, Langone *et al.* 1998).

Moored instruments can provide water column data throughout the year, even when pack ice covers the sea surface in winter. Sediments record environmental conditions at the time of their formation, and the study of sediments can shed light on water column processes. The establishment of a link between water column fluxes measured by traps and sediment deposition and accumulation onto the sea bottom can allow a better understanding of the relative importance of particle sinking processes and the factors that influence particle biogeochemistry and transport. In the framework of the project BIOSESO II (Biogenic Sedimentation in the Southern Ocean), which was focused on the relationship between biogeochemical processes, CO_2 budget, and climate change, particular attention has been dedicated to Ross Sea sediment composition, accumulation and links to water column processes. The aim of this paper is to compare trap fluxes and sediment accumulation at sites D, F, and H (Fig. 1), which are particularly relevant to understanding the formation and transit of deep shelf waters (Jacobs *et al.* 1985). The study presented here also contributes to the project CLIMA (Climatic Long-term Interaction for the Mass Balance in Antarctica).

Study areas

The Ross Sea has a peculiar geomorphology, characterized by a deep and irregular continental shelf, with an average depth of 500 m. The central portion alternates banks (~ 300 m) and basins (> 500 m), characterized by an elongate shape and oriented north to north-east. The shelf slopes towards the continent and is more rugged and deeper on its western side. Near Victoria Land, glacial erosion has

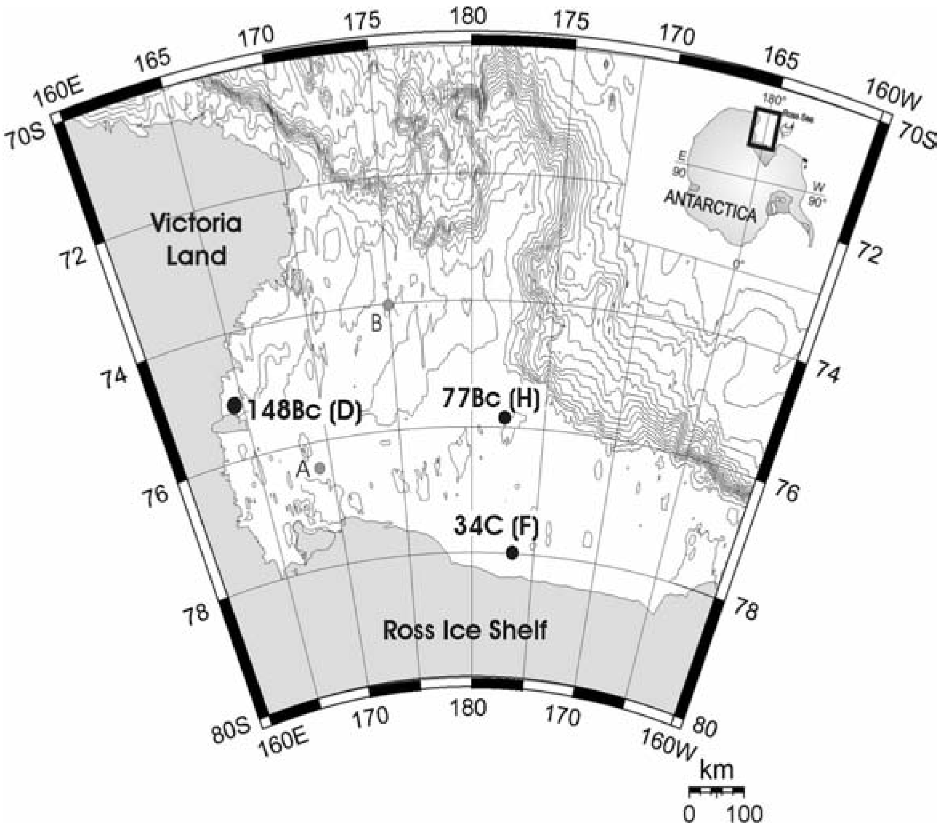


Fig. 1. Study area and sampling sites (D, F, H). The location of other moorings (A and B) in the western Ross Sea is also shown.

created narrow transverse troughs, that can exceed 1000 m depth. This study focuses on three sites, located in the western (site D) and central (sites F and H) sectors of the Ross Sea continental shelf.

Site D is within the polynya of Terra Nova Bay, at 75°06'S and 164°13'E. This is an area of high productivity (Saggiomo *et al.* 2002), although less productive than the southernmost Ross Sea polynya (Smith *et al.* 1996, Smith & Gordon 1997, Goffart *et al.* 2000). The polynya also plays an important role in the production of sea ice (Kurtz & Bromwich 1985) and in the formation of the High Salinity Shelf Water (HSSW), the densest water mass of the whole Southern Ocean (Jacobs *et al.* 1985, Van Woert 1999, Budillon & Spezie 2000).

Site F is located at 77°59'S and 177°01'W, near the edge of the Ross Ice Shelf (RIS). The RIS is the widest floating ice shelf of the Antarctic, covering a surface of about 330 000 km^2. It extends over nearly half the continental shelf and can reach a thickness of 250 m at its northernmost side. The RIS plays a role in the formation of the Ice Shelf Water (ISW).

Site H is located at 75°56'S and 177°36'W, on the outer continental shelf, not far from the shelf break. Sites F and H are positioned along the pathway of the ISW emerging from beneath the RIS and were chosen in order to follow its spreading towards the continental slope.

At the sites reported in this study the chemical constituents (Accornero 1999, Accornero *et al.* 1999, 2003, Martini *et al.* 2001) and biological components (Accornero & Gowin in press, Accornero *et al.* 2000, in press) of water column downward fluxes have been investigated since 1995. Conversely, although sediment texture and composition have been already described (Dunbar *et al.* 1985), biogeochemical processes at the seafloor are poorly known. Surface sediments in the Ross Sea are composed of unsorted ice-rafted debris, siliceous and calcareous biogenic debris and terrigenous silts and clays (Dunbar *et al.* 1985). Coarse terrigenous deposits predominate in Terra Nova Bay (site D), due to the inputs of David and Campbell glaciers. The seafloor of the central outer shelf (site H) is covered by a mixture of ice-rafted debris and fine grained current derived terrigenous sediments, while along the RIS, east of approximately 180° (site F), terrigenous silts and clays make up the bulk of surface sediments (Dunbar *et al.* 1985).

Materials and methods

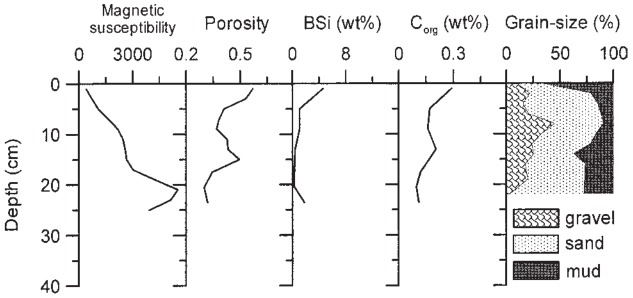
Sediment gravity cores and box-cores were collected at the three sites (Fig. 1) during the 1994/95 Italian Antarctic expedition. In particular, we took gravity core 148c and box core 148bc from near mooring D; gravity core 77c and box core 77bc from site H; and gravity core 34c from site F. Box cores were described and then plastic tubes were inserted into the sediment to obtain several short cores, 24–34 cm long. These short cores, after having been scanned for whole-core magnetic susceptibility, were sub-sampled to

Table I. Conventional ^{14}C ages.

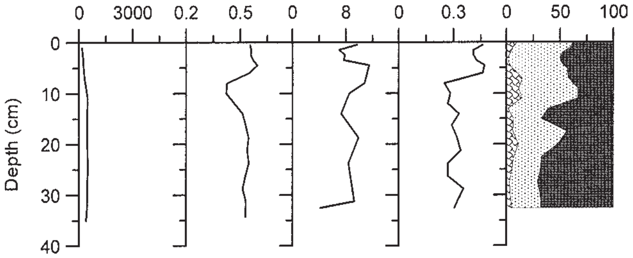
Site (core)	Depth (cm)	^{14}C age (yr BP)	Error (yr)
D (148c)	0–2	4080	50
D (148c)	19–22	15350	100
H (77c)	0–1	8870	35
H (77c)	15–17	14400	60
F (34c)	0–2	7210	40
F (34c)	20–22	30700	190

obtain sediment sections 1–3 cm thick. Following magnetic susceptibility measurements and X-radiography, gravity cores were split in half, visually described and sub-sampled. Parameters measured throughout the sediment cores include porosity, dry bulk density, organic carbon, biogenic silica, and grain size composition.

Box core 148 (site D)



Box core 77 (site H)



Core 34 (site F)

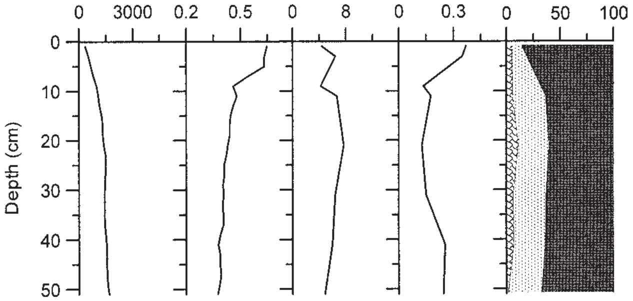


Fig. 2. Depth profiles of whole-core magnetic susceptibility, porosity, biogenic silica and OC concentrations, and grain size composition in box cores 148bc, 77bc and in gravity core 34c.

Table II. Comparison between the composition of the material collected in bottom traps and surficials sediments.

Site	BSi (%)		OC (%)		Si/C (%)	
	trap	sed	trap	sed	trap	sed
D	69.8	7.1	3.6	0.29	19.4	24.6
H	52.9	7.50	10.6	0.46	5.0	16.3
F	44.2	4.5	7.5	0.37	5.8	12.2

Organic carbon (OC) was determined using a Fisons Elemental Analyzer NA2000 after a pre-treatment with 1.5 M HCl to eliminate the carbonate fraction. Biogenic silica (BSi) content was determined through a progressive dissolution method (DeMaster 1981), followed by colorimetric analysis. We used 0.5 M NaOH as an extractant in view of the significant concentrations of biogenic silica usually found in Antarctic samples (DeMaster 1981). The extraction was carried out on 20 mg of sediment at 85°C, taking 0.2 ml aliquots for analysis every hour for 4 hours.

Conventional ^{14}C ages, listed in Table I, were determined by AMS on bulk organic matter. The analyses were carried out by the Woods Hole Oceanographic Institution AMS Facility.

Trap experiments were described by Accornero *et al.* (1999, 2003). The lithic fraction was obtained through the formula: %Lithics = 100 - (%OC × 2) - %BSi - %$CaCO_3$, following Monaco *et al.* (1990). The carbonate component was always negligible in our samples.

Results and discussion

Figure 2 shows the depth distribution of physical properties, such as porosity, magnetic susceptibility and grain size in box cores 148bc (site D), 77bc (site H), and gravity core 34c (site F). Biogenic silica and organic carbon concentration-depth profiles are also displayed. Tables I and II report ^{14}C ages and composition of both trap materials and superficial sediments, whereas Tables III and IV summarize sediment accumulation rates and trap fluxes. We comment mainly on box cores (from sites D and H) because they preserved the topmost part, whereas gravity cores may have lost some surficial sediment. As we do not have a box core from site F, the gravity core is used in this case for the discussion.

Table III. Sediment accumulation rates and mass accumulation rates of particles and biogenic components.

Site	Sediment accumulation rate (cm kyr^{-1})	Mass accumulation flux rate (g m^{-2} yr^{-1})	Surficial opal flux (g m^{-2} yr^{-1})	Surficial OC flux (g m^{-2} yr^{-1})	Lithics (g m^{-2} yr^{-1})
D (148c)	1.73	19.46	1.38	0.056	17.97
H (77c)	1.7	18.80	1.41	0.086	17.22
F (34c)	0.85	7.64	0.34	0.028	7.24

Table IV. Trap flux data. D values from 1995 to 1997 are from Accornero *et al.* (2003), F values for 1995 are from Accornero *et al.* (1999).

site	year	trap	trap depth (m)	water depth (m)	TMF (g m^{-2} yr^{-1})	BSi (g m^{-2} yr^{-1})	OC (g m^{-2} yr^{-1})	Lithics (g m^{-2} yr^{-1})
D	1995–2000	top	180	998	17.85	11.57	0.96	4.36
		bottom	879	998	25.60	17.86	0.92	5.90
H	1995	bottom	530	625	4.44	2.35	0.47	1.15
F	1995–1997	bottom	423	602	7.51	3.32	0.56	3.07

Sediment features

According to the visual description, the topmost sediment of Site D (box core 148bc) was loose mud with traces of bioturbation. The sandy component became prevalent in the subsurficial sediment (representing up to 70%) and the presence of gravels is significant. Here, biogenic silica and organic carbon are very low: BSi reaches 4.5% at the top but decreases to *c.* 1% at depth, whereas organic carbon concentrations range between 0.15 and 0.3%.

At Site H (box core 77bc) the topmost sediment was composed of sandy mud with some organisms at the surface and a few burrows. Clasts were uniformly distributed throughout the sediment. The mud component increased downward with some fluctuations and then remained rather constant from about 23 cm to the bottom. Magnetic susceptibility was low and characterized by only minor changes below 10 cm depth. The highest values of OC characterized the topmost 7 cm whereas biogenic silica peaked at 4.5–8 cm depth (11.5%). While BSi significantly decreased below 35.5 cm depth, OC concentrations remained rather constant between 0.25 and 0.33%.

At site F (gravity core 34c), we retrieved a gravity core, 226 cm long. Figure 2 shows the depth distribution down to 50 cm depth. The surficial sediment (0–4 cm) was a grey mud, whereas a sandy mud, with medium compaction and sparse clasts, prevailed below the core top. OC was 0.37% in the topmost level and decreased to nearly constant levels below 10 cm depth. The surficial value suggested that the core top was preserved in spite of gravity coring. Biogenic silica had a rather constant profile with values in the interval 4–6%.

According to the profiles of Fig. 2, the muddy sediment was maximal at site F and minimal at site D. This can be due to the bottom water currents that may resuspend fine materials and advect them away. Furthermore, the proximity of continental sources can supply coarse sediments at site D. The highest values of magnetic susceptibility were found in box core 148bc at 20 cm depth (Fig. 2), probably due to the direct influence of continental material. Although the sediment is generally finer, the same explanation holds for the high values shown by core 34 whereas the sediment at site H, which is far from direct continental sources, had the lowest magnetic susceptibility.

Surficial sediments (down to 5–10 cm depth) are often characterized by higher values of BSi and OC, due to the recent inputs. These features represent the onset of the seasonally open marine conditions but the differences with respect to the underlying sediment are minor. In fact, surficial concentrations of biogenic silica were relatively low in these samples (4.4–9.7%), compared to other sites of the Ross Sea. For instance, at other mooring sites of the western Ross Sea such as A and B (Fig. 1), biogenic silica concentrations of *c.* 10–30% were measured in surficial sediments by Ravaioli *et al.* (1999). The same authors found values of 0.8–1.2% for OC surficial concentrations.

A comparison between the composition of bottom trap materials (averaged over the years of observation) and surficial sediments is shown in Table II. The decrease in accumulating sediment was 7–10 and 12–23 times for BSi and OC, respectively.

Accumulation rates

We calculated sediment and mass accumulation rates using the time difference between the two conventional ^{14}C ages obtained for each core (Table I). The high radiocarbon ages obtained for organic matter in surficial sediment sections are typical for the Antarctic continental shelves where they range from 1.5 to 10 ka (DeMaster *et al.* 1996). This is due to both the high reservoir effect and to the contamination with old organic carbon that can be supplied from a number of different sources (DeMaster *et al.* 1996, Domack *et al.* 1999). Table III shows calculated sediment accumulation rates, mass accumulation rates and opal, OC and lithics fluxes. Results show that sediment accumulation rates are similar at sites D and H (1.73 and 1.76 cm ka^{-1}, respectively) and much lower at F (0.85 cm ka^{-1}). Mass accumulation rates are 19.46, 18.80 and 7.64 g m^{-2} y^{-1} at D, H and F, respectively.

Mass accumulation rates were used, together with surficial concentrations of biogenic silica and OC, to calculate the fluxes of biogenic particles onto the sediment net of the amounts dissolved/degraded at the sediment water interface (Table III).

Water column fluxes and sediment accumulation

Trap fluxes measured at the sites are summarized in Table IV. Site D was characterized by the highest biogenic silica fluxes by far: 11–17 g m^{-2} yr^{-1} vs 2.35 and 3.32 g m^{-2} yr^{-1} at H and F, respectively. The same pattern was shown by OC even if the difference was much less important

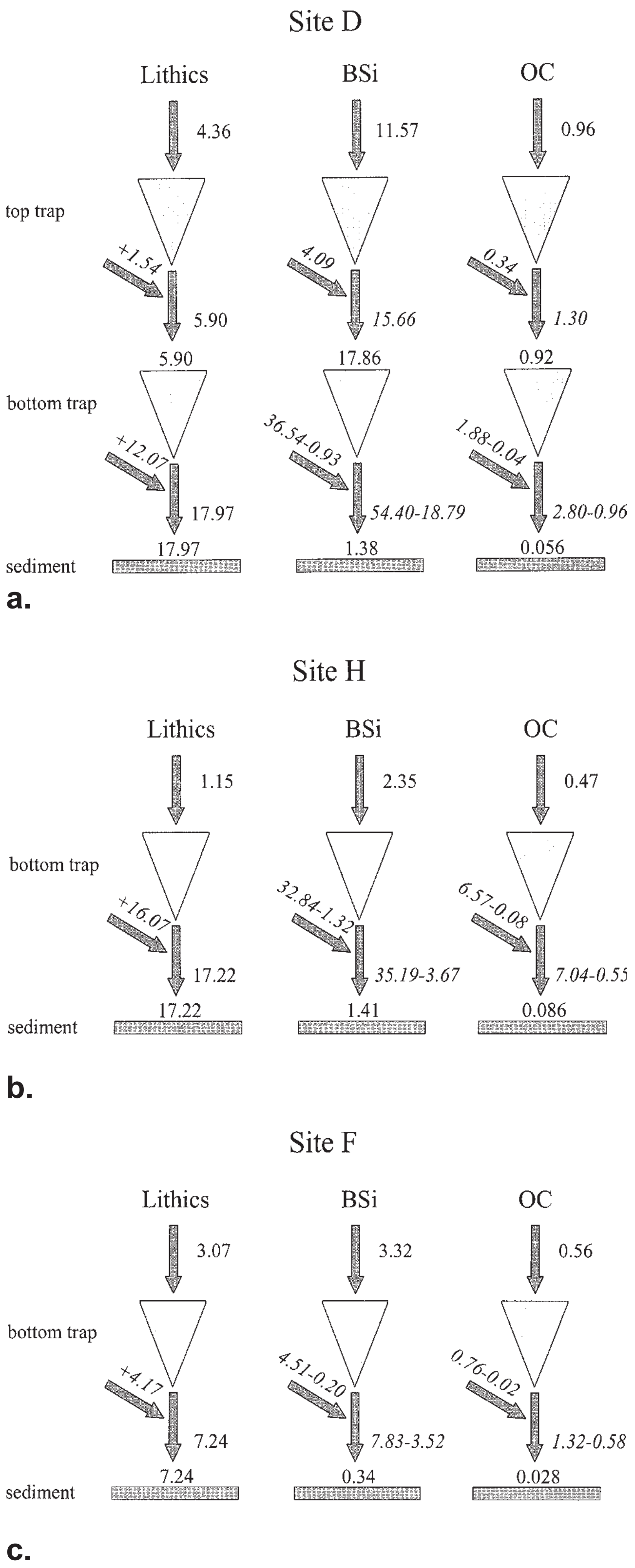


Fig. 3 Water column fluxes and sediment mass accumulation rates of lithics and biogenic components at site D(**a**), H(**b**) and F(**c**). Model calculated values are reported in italics. Only the data relative to the bottom trap are available for sites H and F.

(0.92–0.96 vs 0.47 and 0.56 g m^{-2} yr^{-1}). The differences are likely to result from the different phytoplankton species characterizing the polynya of Terra Nova Bay (TNB) with respect to the area in front of the RIS. In fact, the TNB polynya is a diatom-dominated area (Arrigo *et al.* 1999), although non siliceous algae can largely contribute to the planktonic assemblages in late spring and early summer (Fonda Umani *et al.* 2002). On the contrary, the region near the central RIS is dominated by the prymnesiophyte *Phaeocystis antarctica*, a non siliceous alga whose downward fluxes supply OC-enriched particulates to the bottom sediments (El-Sayed *et al.* 1983, DiTullio *et al.* 2000, Goffart *et al.* 2000). However, even the relatively high fluxes measured at site D were rather low if compared with trap fluxes obtained in other areas of the Ross Sea (DeMaster *et al.* 1992, Dunbar *et al.* 1998, Collier *et al.* 2000). For instance, Dunbar *et al.* (1998) reported fluxes of 9–71 g m^{-2} yr^{-1} of BSi and 1–7 g m^{-2} yr^{-1} of OC, suggesting shelf-wide average values of 30 g BSi m^{-2} yr^{-1} and 5 g OC m^{-2} yr^{-1}.

The availability of both trap and surface sediment data allowed the calculation of the transfer of materials from the water column to the seabed. A model was constructed assuming that lithic particle fluxes are conservative (Fig. 3). In the case of site D (Fig. 3a), the mass balance of lithic particles requires the contribution of laterally advected material between the two traps (1.54 g m^{-2} yr^{-1}) and between the bottom trap and the seabed (12.07 g m^{-2} yr^{-1}). The assumption is that the material advected to the bottom trap has the same composition as the material collected by the upper trap. Therefore, the advected BSi and OC fluxes were calculated using the advected flux of lithics and the ratio of lithics and biogenic materials in the trap. For example, taking into account the OC at site D, an extra flux of 0.34 g m^{-2} yr^{-1} is required between the two traps following the indication obtained from the lithics: the sum of this flux with that measured by the upper trap gives an estimate of 1.30 g m^{-2} yr^{-1}. However, the bottom trap measured 0.92 g m^{-2} yr^{-1}, and this requires the degradation of 29% of the total. The same approach was used for the bottom trap-sediment system. In this case the assumption is that the advected material is either similar to the material of the bottom trap (giving a flux of 1.88 g m^{-2} yr^{-1}) or to the surface sediment (supporting a flux of 0.04 g m^{-2} yr^{-1}). The amount of OC preserved in the lower part of the water column is 2% or 5.8%, according to the hypothesis chosen for the composition of the advective flux. The preservation is 1.4 and 4.1% with respect to the composition of the sediment recovered by the upper trap. This means that the maximum degradation occurs between the bottom trap and the sediment and/or within the surficial sediment. The slight discrepancy observed for BSi between the two traps (the calculated flux is lower than the measured one) can be due to the uncertainties affecting measured data and assumptions.

Model calculations show that lateral advection is always required to balance vertical fluxes and the effects of dissolution/degradation processes, as shown also by Fig. 3b & 3c. Nelson *et al.* (1996) estimated that for the whole Ross Sea preservation is 21.5% and 4.9% for silica and organic carbon, respectively. From our data BSi preservation with respect to the bottom trap is 2.5–7.3, 4–38, and 4.3–9.7% at sites D, H and F, respectively. On the other hand 2–5.8, 1.2–15.6, and 2.1–4.8% of organic carbon are preserved at the same sites. The average values for BSi and OC are similar, thus suggesting a lower degree of decoupling of the two cycles. The low preservation of biogenic components could be due to the low sediment accumulation rate that enhance the residence time of biogenic materials in the proximity of the sediment-water interface. This effect also explains why the biogenic material sinking through the water column has a scarce influence on the sediment at the three sites.

In addition, the sinking of particles can be strongly affected either by strong currents that can transport particles away from the site of formation (Jaeger *et al.* 1996) or by the vertical displacement of isopycnal surfaces as suggested by Accornero *et al.* (1999) for site F. However, the fluxes recorded by the upper trap at site D are low if compared to other sites of the Ross Sea and this can be due to the effects of lower production and/or physical control over the sinking process.

Conclusions

The characteristics of the sediment at three mooring sites in the Ross Sea were studied. Even though these areas are productive, the water column fluxes and the accumulation of BSi and OC in sediments are low. The apparent lack of export efficiency depends on the relative importance of production, removal and dissolution/degradation processes. Furthermore, the preservation of biogenic components appears lower than at other mooring sites of the Ross Sea, probably due to the low sediment accumulation rates and, consequently, the high residence time in the surficial sediment. A simple model was constructed assuming a conservative behaviour of the lithics through the water column. The contribution of advected material is necessary to account for the mass balance of both lithic and biogenic components. Results show that lateral advection is higher close to the bottom. The preservation of both BSi and OC is higher at site H than at sites D and F.

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