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Water column features and their relationship with sediments and benthic communities along the Victoria Land coast, Ross Sea, summer 2004

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Abstract: The northern Victoria Land coastal marine environment was investigated during the late summer 2004, within the framework of the Latitudinal Gradient Project (LGP), to describe the physical, chemical and biological patterns of the water column and their relationship with the pelagic and benthic compartments, and to determine to what extent they change with latitude. A latitudinal gradient from Cape Adare to the Terra Nova Bay–Cape Russell area was determined on the basis of abiotic and trophic factors. Cape Adare had lower values of organic matter (particulate organic carbon < 150 µg l^{-1}) available for the benthic communities, but this organic matter had good trophic quality. In Terra Nova Bay the particulate organic matter was quantitatively higher (organic carbon > 400 µg l^{-1}), presumably reaching the bottom via faecal pellets, but was more detrital, although its nutritive value was still high (carbon protein content nearly 40%), as confirmed by the great quantity of phytopigments in the sediments (> 4.0 µg g^{-1}). The benthic communities changed with latitude as well, partially reflecting the environmental and trophic gradient, but also showing a large within-area variability (except for the Cape Adare area), due to a complex array of variables that did not change with latitude.

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Key words: Antarctica, Latitudinal Gradient Project, pelagic-benthic coupling

Introduction

The coast of Victoria Land, from Cape Adare (71°S) to McMurdo Sound (78°S), represents the most extensive latitudinal gradient in Antarctica after the Antarctic Peninsula, with an unmatched variety of marine, terrestrial and freshwater habitats. This latitudinal span is accompanied by major north–south gradients in environmental properties (e.g. annual radiation, duration of melt, air temperature, day length, ice cover, trophic inputs) which are likely to exert a large influence on ecological processes.

The overall goal of the multinational and multidisciplinary Latitudinal Gradient Project (LGP) was to take a latitudinal gradient approach to both terrestrial and marine ecosystem studies in Victoria Land, and to study the role of latitude in determining the main features of the littoral ecosystems (Berkman *et al*. 2005). In particular, this study addresses the question of to what extent ecosystem structure and function (diversity/complexity) change with latitude (Howard-Williams *et al*. 2006).

The Ross Sea is one of the most productive areas of the Southern Ocean (Smith & Nelson 1985, Nelson *et al.* 1996, Smith & Gordon 1997) and shows high spatial, seasonal and interannual variability in the quantity and quality of the organic matter in the water column (Nelson & Smith 1986, Fabiano *et al*. 1993, 1996, Povero *et al.* 2000), due to sea ice dynamics and meteorological conditions (Saggiomo *et al.* 2000, Arrigo & van Djiken 2004). Exceptional events, such as big iceberg calvings (Arrigo *et al.* 2002, Arrigo & van Djiken 2003), can also have an impact on the general circulation and sea ice dynamics. Primary production, together with sediment release from glaciers and sea ice melting, is the main source of the settling particles in this marine environment (Baldwin & Smith 2003, Isla *et al.* 2006) and variations in fluxes during the summer (Nelson *et al.* 1996) modify the transfer of organic matter, the most important energy source for benthic organisms, from the pelagic domain to the bottom.

Although differences in the distribution and ecology of benthic communities are determined by many factors, such as bottom features and morphology, iceberg scouring and food availability (Dayton 1990, Gutt *et al.* 1996, Arntz *et al.* 1997, Cattaneo-Vietti *et al.* 1999, Thrush *et al*. 2006), pelagic-benthic coupling is considered the most important

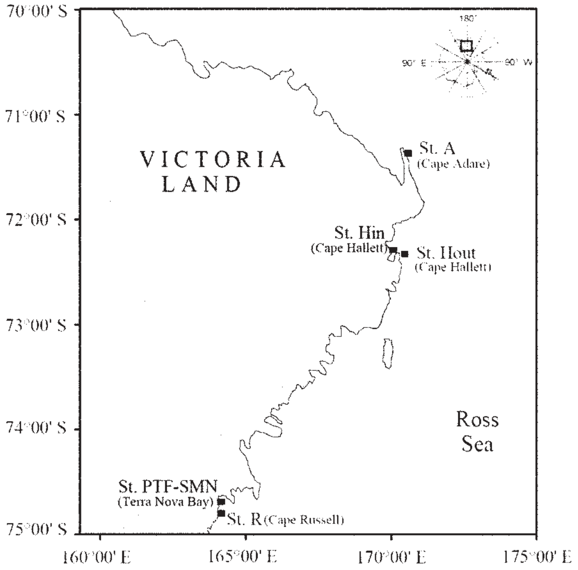

Fig. 1. Sampling area and station locations.

factor in structuring benthic communities in high latitudes (Fabiano *et al*. 1997, Piepenburg *et al*. 1997, Cattaneo-Vietti *et al.* 1999, Povero *et al.* 2001).

Previous studies of benthic pelagic coupling in the coastal zone of the central and northern Victoria Land were carried out in Terra Nova Bay (TNB), and showed a close link between the biochemical composition of the organic matter in the water column and the material that accumulated in sediment traps and sediments, which came from interactions between physical (break up and melting of the ice cover, effect of katabatic winds) and biological processes (related to primary producers and grazers; Fabiano *et al.* 1997, 2000a, Pusceddu *et al.* 2000, Povero *et al.* 2001). Little is known about the area north of TNB, because previous oceanographic research was focused offshore (Gordon *et al.* 2004) or in the central part of the basin (Smith & Nelson 1985, Fabiano & Danovaro 1998, Collier *et al.* 2000, Fabiano *et al.* 2000b, Povero *et al.* 2000).

The aim of this study was to provide a "snapshot" of the physical, chemical and biological properties of the coastal water column of the Ross Sea, between the depths of 100 and 500 m, along the latitudinal gradient from Cape Adare to Cape Russell, during late summer, and to investigate the trophic relationship between the pelagic and benthic compartments.

Materials and methods

Study area and sampling

The sampling area extended along the coast of Victoria Land from 71°S to 74°S (Fig. 1). Samplings were performed at Cape Adare (71°19'S), Cape Hallett (72°17'S), Terra Nova Bay (74°43'S) and Cape Russell (74°50'S). Samplings were taken between depths of 100 and 500 m at 15 stations from 4–22 February 2004 (Table I). At Cape Hallett samplings were taken on both the inner and outer sides of the Cape. The water column data were pooled, without reference to the side, while the sediment data are reported separately for the two sides. During most of the sampling period the sea was free of sea ice at Cape Adare and Cape Hallett, while in the southern areas sea ice was reforming.

Analytical methods

Temperature, salinity and fluorescence data were collected from the RV *Italica* with a Sea Bird 25 probe and a SCUFA fluorometer. Water samples were collected from the surface to the bottom (6 to 8 depths) using Niskin bottles arranged on a Carousel SBE 32 sampler. After retrieval, the samples were immediately taken to the laboratory. The water samples to be used for the inorganic nutrient analyses

Table I. Sampling locations, bottom depth (m), sea-ice situation, water column temperature and salinity at the sampling stations.

Stations	Lat. S	Long. E	Area	Depth (m)	Sea ice situation	Temperature (°C) max–min	Salinity (psu) max–min
A3	71°18.2'	170°32.9'	Cape Adare	300	ice free	-0.91 ± -1.28	34.57 ± 34.15
A4	71°18.8'	170°29.0'	Cape Adare	200	ice free	-1.20 ± -1.28	34.37 ± 34.24
A5	71°18.7'	170°26.9'	Cape Adare	100	ice free	-1.24 ± -1.40	34.34 ± 34.19
Hin2	72°17.2'	170°11.4'	Cape Hallett	400	breaking ice	-1.35 ± -1.61	34.60 ± 33.96
Hin4	72°17.6'	170°12.4'	Cape Hallett	200	breaking ice	-1.45 ± -1.60	34.61 ± 34.06
Hin5	72°17.7'	170°13.1'	Cape Hallett	120	breaking ice	-1.34 ± -1.48	34.41 ± 34.02
Hout1	72°15.9'	170°29.2'	Cape Hallett	500	ice free	-0.51 ± -1.27	34.63 ± 34.19
Hout3	72°16.6'	170°26.5'	Cape Hallett	350	ice free	-1.00 ± -1.73	34.69 ± 34.03
Hout4	72°17.2'	170°23.7'	Cape Hallett	200	ice free	-1.05 ± -1.68	34.63 ± 34.19
Hout5	72°17.8'	170°19.4'	Cape Hallett	100	ice free	-1.37 ± -1.38	34.07 ± 33.92
PTF	74°42.1'	164°09.3'	Terra Nova Bay	200	frazil ice	-1.06 ± -1.98	34.72 ± 33.88
SMN	74°42.9'	164°13.3'	Terra Nova Bay	385	frazil ice	-0.83 ± -1.99	34.73 ± 33.88
R2	74°50.6'	164°19.1'	Cape Russell	371	frazil ice	-1.00 ± -2.01	34.74 ± 33.90
R3	74°49.8'	164°14.0'	Cape Russell	300	frazil ice	-1.24 ± -2.00	34.73 ± 33.92
R4	74°49.8'	164°06.1'	Cape Russell	200	frazil ice	-1.66 ± -1.88	34.68 ± 34.03

(nitrates and phosphates) were prefiltered with polycarbonate filters. The samples for the suspended particulate matter determinations (organic carbon and nitrogen, proteins, carbohydrates, and chlorophyll *a*) were collected on GF/F filters. They were then stored at -80°C. The water samples (50 ml) for assessing the bacterioplankton abundance (BA) were preserved with buffered-formaldehyde (2% final concentration) and refrigerated. The samples were processed within 40 days of sample collection. Appropriate volumes were filtered though 0.2 µm black Nuclepore filters and stained with DAPI according to Porter & Feig (1980). The filter was mounted on a slide with Cargille type-A non-fluorescent immersion oil. The bacteria were analysed with a Zeiss Axioplan 2 Imaging epifluorescence microscope equipped with an Axiocam digital camera (Zeiss) and digitised using Axiovision 3.1 software. A minimum of 250 cells and 25 fields of view were counted.

The nutrient determinations were carried out following Hansen & Grasshoff (1983) with a Technicon II AutoAnalyzer. After the removal of the carbonates with HCl vapour in a desiccator (Hedges & Stern 1984, Tanoue 1985), the particulate organic carbon and nitrogen (POC and PON) were analysed by combustion using a CHNS-O EA1108 Elemental Analyzer (Carlo Erba). Proteins (PPRT) were calculated using the Lowry procedure modified by Hartree (Hartree 1972) and using bovine albumin as standard. The carbohydrates (PCHO) were determined after Dubois *et al*. (1956) with D-glucose as standard. They were expressed in carbon equivalents (each fraction was multiplied by 0.49 and 0.4, respectively for PPRT and PCHO). The chlorophyll *a* (Chl *a*) in the water column was determined by HPLC analyses and used to calibrate the probe fluorescence signal. The HPLC analyses were performed (Hewlett Packard HPLC mod. 1100) according to Vidussi *et al.* (1996).

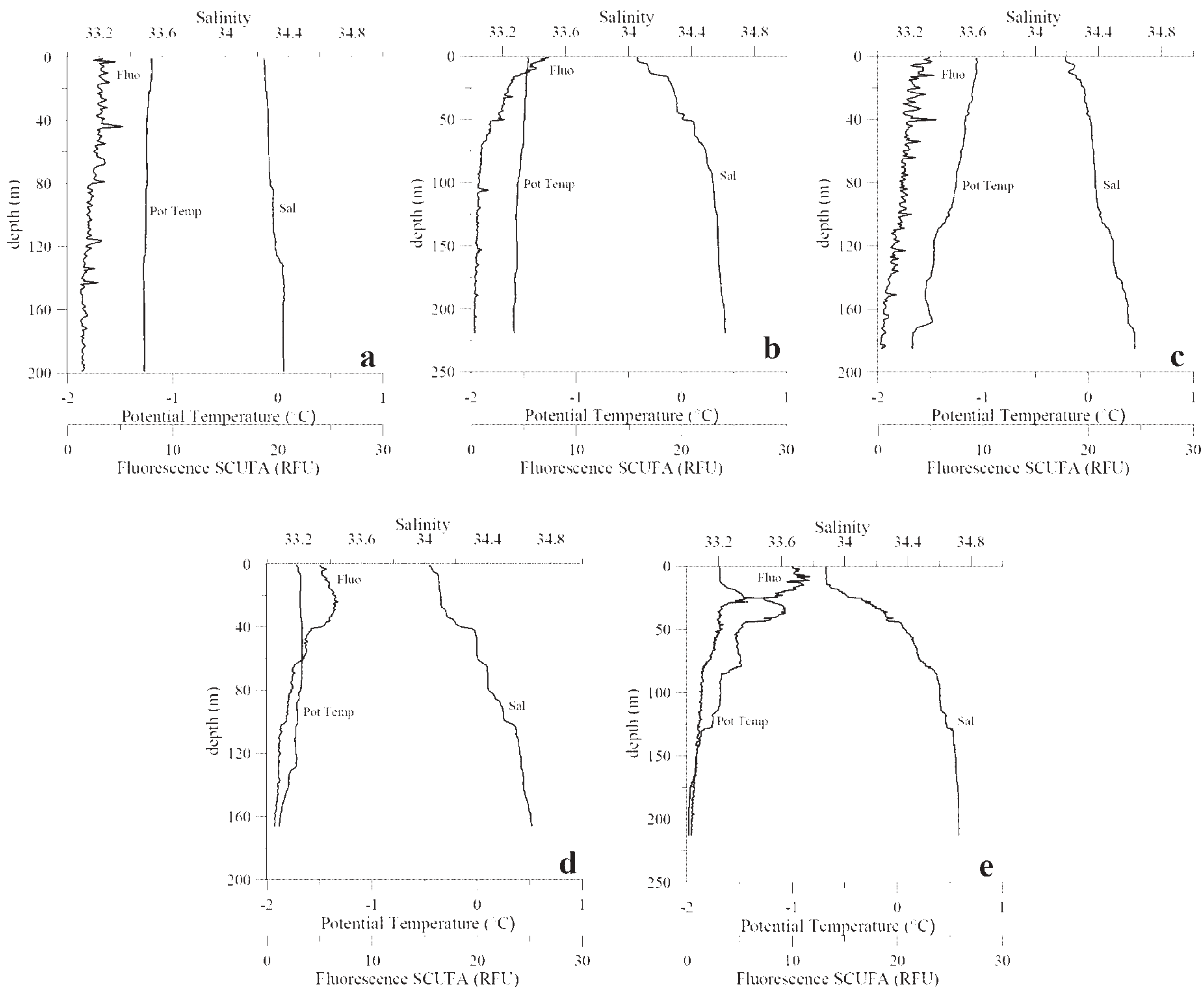

Fig. 2. Vertical distribution of temperature, salinity and fluorescence in the different coastal areas of Victoria Land (bottom 200 m; **a.** Cape Adare, **b.** Cape Hallett in, **c.** Cape Hallett out, **d.** Cape Russell, **e.** Terra Nova Bay).

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The sediment samples were collected using a Van Veen grab, and the analyses were carried out on the upper layer of triplicate sediment aliquots. The Chl *a* and phaeopigments (Phaeo) were analysed following Lorenzen & Jeffrey (1980) with a Varian spectrophotometer and the total organic matter (AFDW) was determined by loss on ignition (450°C) (Parker 1983).

The particle size profiles were determined by dry-sieving analysis, after the removal of organic matter with a hydrogen peroxide solution (10%), and a set of standard sieves (Endecotts Ltd.) The sieve mesh decreased at regular size intervals from -1 Φ (2000 μm) to 4 Φ (62.5 μm) (Wentworth 1922). Data were expressed as a percentage of each weighed fraction.

The benthic organisms were collected using an Agassiz Trawl (AGT, one sample from each station) and Van Veen grab (60 l in volume, three samples at each station), at depths ranging between 84 and 537 m (Ramorino 2004).

The statistical analyses were carried out using a Statistica package (StatSoft 1995). Student's *t*-test was used to compare the two sets of data: sample mean in the upper (0–25 m) and in the deeper (26 m–bottom) layer of the water column in a specific area, or sample mean in two areas, or two groups of stations (Cape Adare–Cape Hallett pooled together, and Cape Russell–Terra Nova Bay pooled together) in the upper or in the deeper layer of the water column, or in the sediments.The correlation-based principal component analysis (PCA) was carried out on two datasets: the first one including the potential environmental and trophic features of the water column and sediments, and the second one composed of data on the benthic communities as well as the previous dataset. All the values were normalized prior to the PCA.

Results

Physical structure

Different hydrological conditions were observed along the coast of Victoria Land (Fig. 2, Table I). In the Cape Adare area all the stations showed great homogeneity throughout the water column. The water column stratification increased from Cape Hallett towards the south (Fig. 2) and isolated the upper layer (0–25 m) from the deeper layer (26 m–bottom). The surface temperature was below 0°C in all the areas, but lower values were registered in the southern areas (upper layer mean values < -1.50°C), while the salinity decreased from a mean value of 34.21 psu at Cape Adare to 34.00 psu in the TNB area. The lowest temperature and the highest salinity values (T < -1.80°C and salinity > 34.50 psu) occurred below the 100–200 m depth at Cape Russell and in Terra Nova Bay.

Chemical and biochemical features

The chemical and biochemical variables were pooled separately for the upper (0–25 m) and the deeper (26 m–bottom) depths as the physical data highlighted the separation of the water column into two layers. The mean

Table II. Chemical, elemental and biochemical composition of the seawater and particulate suspended matter in the different areas of the Victoria Land Transect. The following data are reported: average, standard deviation and number of observations (n) of nutrients, particulate organic carbon and nitrogen (POC and PON), particulate proteins (PPRT) and carbohydrates (PCHO), photosynthetic pigments and bacterial abundance (BA) in surface layer (0–25 m) and deeper layer (26 m–bottom).

0–25m		Cape Adare (*n* = 8–14)		Cape Hallett (*n* = 21)		Terra Nova Bay (*n* = 3–6)		Cape Russell (*n* = 6–9)	
		avg	std	avg	std	avg	std	avg	std
nitrates	μM	21.18	2.53	19.61	4.54	13.28	2.21	14.31	3.80
phosphates	μM	1.74	0.36	1.29	0.37	0.77	0.45	0.41	0.16
POC	μg C l^{-1}	131.1	39.8	241.1	74.1	451.1	137.4	323.6	76.8
PON	μg N l^{-1}	20.2	7.7	30.3	5.3	73.2	21.1	61.4	15.3
PPRT	μg C l^{-1}	61.9	44.9	83.6	10.7	164.3	38.3	153.2	36.2
PCHO	μg C l^{-1}	54.1	44.9	82.3	36.9	122.1	45.6	67.8	11.6
Chl *a*	μg l^{-1}	0.43	0.22	0.99	0.22	1.29	0.38	1.23	0.33
BA	cell/ ml	66 497	24 978	88 249	36 424	184 333	118 889	138 521	40 557
26 m–bottom		**Cape Adare (*n* = 7–12)**		**Cape Hallett (*n* = 23)**		**Terra Nova Bay (*n* = 7–12)**		**Cape Russell (*n* = 4–8)**	
		avg	std	avg	std	avg	std	avg	std
nitrates	μM	22.49	2.08	25.03	3.93	25.06	5.12	19.61	7.12
phosphates	μM	1.97	0.46	1.94	0.47	2.05	0.49	1.10	0.45
POC	μg C l^{-1}	116.6	34.1	134.9	56.5	118.4	85.2	110.4	58.6
PON	μg N l^{-1}	15.7	4.8	15.3	8.4	15.4	11.7	15.8	11.6
PPRT	μg C l^{-1}	40.0	12.0	39.4	19.9	42.0	28.7	45.7	33.4
PCHO	μg C l^{-1}	43.1	24.0	51.1	27.6	54.7	42.8	41.0	21.5
Chl *a*	μg l^{-1}	0.43	0.16	0.41	0.34	0.18	0.18	0.24	0.17
BA	cell/ ml	102 019	86 673	60 622	31 040	53 069	27 375	104 501	50 678

Table III. Sediment particle size at the different sampling stations of the Victoria Land Transect (% Φ = -1, 2000.0 µm, % Φ = 0, 1000.0 µm, % Φ = 1, 500.0 µm, % Φ = 3, 125.0 µm, % Φ = 4, 62.5 µm, % Φ > 4, < 62.5 µm).

stations	% Φ = -1	% Φ = 0	% Φ = 1	% Φ = 3	% Φ = 4	% Φ > 4
A3	45.51	15.62	9.08	27.93	1.68	0.19
A4	29.91	10.38	14.32	41.82	3.03	0.55
A5	33.29	14.81	11.49	37.21	2.81	0.40
H2 in	16.36	1.78	2.28	50.09	23.00	6.49
H4 in	9.13	3.28	4.23	42.47	29.69	11.21
H5 in	33.11	1.35	1.46	39.56	17.60	6.92
H1 out	21.84	11.80	10.92	33.68	14.84	6.92
H3 out	40.28	8.05	7.91	22.75	13.58	7.43
H4 out	60.47	8.28	4.21	12.50	10.31	4.23
H5 out	23.25	10.98	15.23	40.55	8.18	1.81
SMN	5.44	0.00	7.65	66.29	19.78	0.85
R3	0.00	0.22	4.77	62.63	30.76	1.62
R4	25.44	15.49	13.43	31.11	12.78	1.75

values of the nutrients, particulate organic carbon and nitrogen, proteins and carbohydrates, photosynthetic pigments and bacterial abundance of the two layers in the different areas are summarized in Table II. At Cape Adare, these parameters did not show any significant difference between the upper and the deeper layer (Student's *t*-test, $P < 0.09$), with the exception of the PPRT (higher in the upper layer, $P < 0.005$). Moving southwards, differences between the two layers became more evident, with lower nutrient concentrations and higher POM and bacterial abundances in the upper layer (*t*-test, $P < 0.007$, with the exception of the bacterial abundance in TNB and the nitrate abundance at Cape Russell).

The inorganic nutrients (nitrates and phosphates) were generally high. They reached their lowest levels in the southern areas (7.82 µM for nitrates and 0.21 µM for phosphates at Cape Russell) and their highest in the deeper layer of all the stations of the study area (nitrates > 13.28 µM and phosphates > 1.00). In the upper layer (0–25 m) the mean concentrations were generally higher in the two northern areas (Cape Adare and Cape Hallett) than in Terra Nova Bay and at Cape Russell (*t*-test, $P < 0.001$).

The particulate organic matter in the upper layer of the water column showed an increasing trend from north to south (the POC increased 2.5-fold from Cape Adare to TNB, while the PON increased by around 3-fold). Thus the POC and PON concentrations in the upper 25 m layer in the Cape Adare and Cape Hallett areas were lower and statistically different from those in the other areas (*t*-test, $P < 0.0001$). Similarly, the PPRT concentrations, directly related to the PON ($P < 0.001$), were higher in the southern areas ($P < 0.001$), while the PCHO concentrations did not show any latitudinal trend. In the deeper layer, the particulate organic matter concentration was lower and showed similar values in the different areas. The Chl *a* reached its maximum values in the upper layer, especially in the southern areas (1.90 µg l^{-1} and 1.70 µg l^{-1} in TNB and at Cape Russell, respectively). As with the POC and PON, the Chl *a* concentrations at Cape Adare were significantly lower (0.43 µg l^{-1}) than in any of the other areas, which were close to or higher than 1.00 µg l^{-1} (*t*-test, $P < 0.0001$). The phytopigment concentrations in the deeper layer, were higher in the north than in the south (*t*-test, $P < 0.006$), but the mean concentration was not higher than 0.50 µg l^{-1}.

The bacterial abundance showed the highest values in the upper layer (>120 000 cell ml^{-1}) and in the southern areas, where it was higher than in the two northern areas (*t*-test, $P < 0.0001$). In the deeper layer it dropped to values < 100 000 cell ml^{-1}, with a few exceptions at Cape Adare.

Sediments

The sediment particle size composition showed differences between the areas. Coarse sediments dominated at Cape Adare and Cape Hallett while, moving south, medium and fine sands increased (in Terra Nova Bay and at Cape Russell, Table III). A minor silt-clay fraction was found in the Cape Hallet area, co-existing with coarse sediments in the outer area, and with sand in the inner area.

The organic carbon content of the sediments had values ranging between 0.011 and 0.041 g g^{-1} at Cape Adare and Cape Hallett but did not reach 0.010 g g^{-1} in the southern area (Cape Russell and TNB) (Table IV).

The Chl *a* in the sediments had similar concentrations at Cape Adare and Cape Hallett and a slightly higher concentration at Cape Russell (mean value for the three areas: 0.6 µg g^{-1}), and it reached its maximum in Terra Nova Bay (3.86 µg g^{-1}). Phaeopigment concentrations also increased moving southwards from Cape Adare (0.78–1.05 µg g^{-1}). The maximum value occurred at Cape Russell (5.79 µg g^{-1}) (Table IV). Thus, the two northern areas had lower phytopigment concentrations (*t*-test, $P < 0.02$).

Table IV. Sediment photosynthetic pigments and organic fraction (AFDW) in the different areas of the Victoria Land Transect.

sediments		Cape Adare		Cape Hallett in		Cape Hallett out		Terra Nova Bay		Cape Russell	
		avg	std	avg	std	avg	std	avg	std	avg	std
Chl *a*	µg g^{-1}	0.49	0.35	0.55	0.00	0.67	0.43	3.86	1.11	0.62	0.59
Phaeo	µg g^{-1}	0.96	0.86	2.93	0.19	1.28	0.38	4.49	0.81	5.71	0.11
AFDW	g g^{-1}	0.020	0.008	0.026	0.013	0.021	0.012	0.006	0.005	0.006	0.002

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Table V. Littoral biomass percentages at the different sampling stations of the Victoria Land Transect.

stations	A3	A4	A5	H2in	H4in	H5in	H3out	H4out	H5out	SMN	R2	R3	R4
Depth (m)	300	200	100	400	200	120	350	200	100	385	371	300	200
Ascidiacea	0.6	45.7	11.4	0.0	0.0	0.0	1.8	0.0	7.2	0.0	0.0	0.0	0.0
Bryozoa	6.2	0.0	75.1	65.9	5.9	39.4	91.5	70.2	34.0	12.8	17.5	36.3	19.4
Crustacea	12.7	4.4	0.0	0.0	0.0	0.0	3.0	0.0	12.7	0.0	0.0	0.0	0.0
Cnidaria	0.0	0.0	0.0	0.0	0.3	1.8	0.0	3.1	3.0	50.1	23.4	0.0	0.0
Echinodermata	3.9	39.9	3.1	34.1	20.6	8.0	1.9	23.1	27.8	24.2	34.4	28.7	8.1
Mollusca	0.0	0.0	0.0	0.0	0.0	31.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0
Pantopoda	0.0	0.0	3.4	0.0	0.8	0.3	0.9	0.0	5.3	0.0	0.0	0.0	0.0
Polychaeta	0.0	0.0	0.0	0.0	13.5	0.0	1.0	0.7	0.0	11.7	15.6	0.0	0.0
Porifera	76.6	9.9	6.9	0.0	51.4	19.6	0.0	2.6	10.1	1.2	7.6	35.0	0.0
Hemicordata	0.0	0.0	0.0	0.0	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	72.5

Benthic community

The biomass percentages at each station are summarized in Table V. At Cape Hallett and Cape Adare, the benthic communities were characterized by dense populations of bryozoan mats and ascidians (the latter only at Cape Adare). Generally, echinoderms (particularly ophiuroids) were abundant, while, locally, other taxa dominated, such as sponges and *Cephalodiscus* spp. (Hemicordata), which reached high densities only at Cape Russell at a depth of 200 m. In accordance with an increase in the mud fraction, the communities showed an increase in polychaetes and ophiuroids (Deep Shelf Mud Bottom Assemblage).

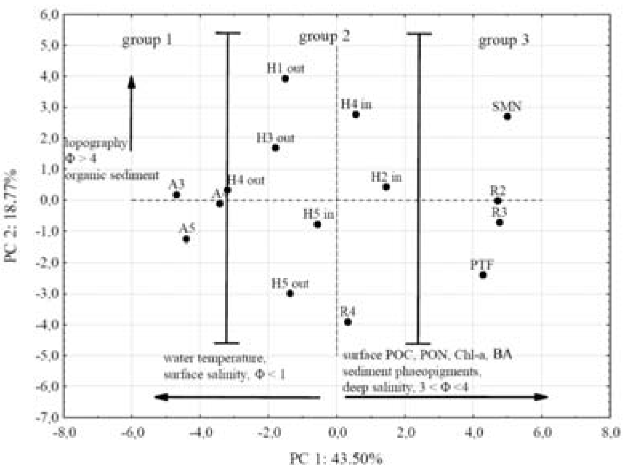

Fig. 3. Principal component analysis (PCA) of the potential trophic and environmental determinants of the water column (integrated 0–25 m and 25 m–bottom) and sediments. *Abiotic characterization of the different areas*: bottom topography, water temperature and salinity, sediment particle size ($-1 < \Phi < 4$–$2000\ \mu m < \Phi < 63\ \mu m$). *Trophic status of the areas and potential food source for the benthos*: phosphate depletion and nitrate depletion [i.e. phosphate and nitrate concentrations, being subtracted from the maximum concentration of the areas, 2.59 µM for phosphates and 34.47 µM for nitrates) were used as an estimate of phytoplankton assimilation (Povero *et al.* 2000) in the different areas and as a proxy of export production, despite the potential for the results to be confounded by multiple source water signatures]; water column pigments, particulate organic carbon and nitrogen, bacterial abundances; sediment pigments and organic carbon.

Principal Component Analyses

The PCA analysis of the trophic and environmental parameters in the water column and sediments (Fig. 3, Table VI) identified two significant components, explaining the 43.50% and the 18.77% of the total variance, respectively. A clear gradient along the first axis defined three groups of stations: Cape Adare, Cape Hallett and TNB-Cape Russell.

They differed because of the physical features of the water column (e.g. warmer waters in the north and colder waters in the south), sediment particle size that became finer southwards, and phosphate and nitrate depletion, the quantity of the organic matter in the upper layer that increased southwards, together with water bacterial abundance and sediment phaeopigments.

The second principal component (PC2) highlighted the

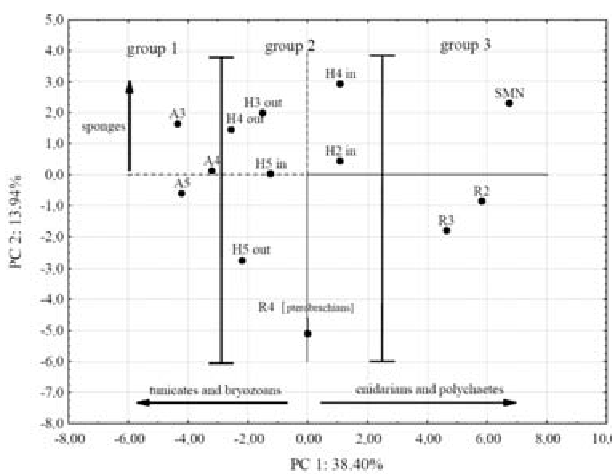

Fig. 4. Principal component analysis (PCA) of the potential trophic and environmental determinants of the water column, sediments and benthic communities.

Table VI. Principal component analysis (PCA): Factor-variable correlations (factor loadings).

	PCA 1 (Fig. 3)		PCA 2 (Fig. 4)	
	PC 1	PC 2	PC 1	PC 2
topography	0.35	0.68	0.62	0.34
surface N depletion	0.78	0.12	0.75	0.02
deep N depletion	-0.06	-0.79	-0.20	-0.74
surface P depletion	0.73	-0.45	0.63	-0.54
deep P depletion	0.22	-0.79	0.10	-0.83
surface POC	0.89	-0.01	0.88	-0.14
deep POC	-0.11	-0.60	-0.50	-0.54
surface Chl *a*	0.87	0.19	0.88	-0.03
deep Chl *a*	-0.64	-0.44	-0.80	-0.10
surface PON	0.94	-0.12	0.93	-0.22
deep PON	-0.10	-0.83	-0.50	-0.71
surface BA	0.84	0.11	0.88	-0.10
deep BA	-0.08	-0.49	-0.04	-0.51
surface temperature	-0.67	0.55	-0.72	0.53
deep temperature	-0.91	0.23	-0.93	0.28
surface salinity	-0.77	0.26	-0.68	0.24
deep salinity	0.79	0.33	0.86	0.08
sediment Chl *a*	0.69	0.14	0.68	0.27
sediment Phaeo	0.82	-0.45	0.76	-0.53
sediment organic matter	-0.18	0.42	-0.19	0.41
% Φ = -1	-0.82	-0.01	-0.78	0.16
% Φ = 0	-0.78	-0.22	-0.78	-0.32
% Φ = 1	-0.36	-0.32	-0.41	-0.46
% Φ = 3	0.82	-0.05	0.78	-0.07
% Φ = 4	0.81	0.22	0.81	0.09
% Φ > 4	-0.07	0.53	0.04	0.44
Ascidiacea			-0.38	-0.05
Bryozoa			-0.26	0.08
Crustacea			-0.48	-0.06
Cnidaria			0.70	0.24
Echinodermata			0.44	-0.05
Mollusca			-0.10	0.01
Pantopoda			-0.37	-0.27
Polychaeta			0.68	0.35
Porifera			-0.17	0.29
Hemicordata			0.01	-0.64

differences between the stations within each area. In particular, Cape Adare showed a greater homogeneity, while the other areas had a greater variability, due in particular to depth.

Adding the biomass percentage data to the previous dataset (Fig. 4, Table VI), two significant components were identified, explaining the 38.40% and the 13.94% of the total variance, respectively. The three groups of stations were still evident. Along the first principal component, cnidarians and polychaetes added a positive contribution, while tunicates and bryozoans a negative one. The Cape Adare stations showed a close similarity, while in the other areas, the scatter between the stations within areas was higher. Sponges contributed to PC2. Some specific communities (e.g. pterobrachians) characterised single stations.

Discussion

This work is the first multidisciplinary investigation of the marine area of Victoria Land, from shallow waters to a maximum depth of 500 m.

The processes occurring in the water column may change faster than those in the sediments and benthic communities and, thus, our water column data only represent a "snapshot" of the sampling date, but they are in good agreement with those reported in literature for the different areas considered. In fact, literature data for the different zones and latitudes of the Ross Sea for different periods or sea ice conditions, reported in Table VII, show a good fit with our data. However, these data refer to the offshore area and little is known of the marine environment of the northern coast of Victoria Land, because previous

Table VII. Literature data (photosynthetic pigments, primary production, nitrates and particulate organic carbon-integrated in the euphotic zone) for the different zones and latitudes of the Ross Sea, in different periods or sea-ice conditions.

	Chl *a* $\mu g\ l^{-1}$	Primary production mg C $m^{-2}\ d^{-1}$	Nitrates µM	POC $\mu g\ l^{-1}$	Period	References
N Ross Sea (71–73°S)						
	0.50 (0.30)	387 (163)	-	-	Summer	Saggiomo *et al.* 2002
	0.6–0.9	-	25.0–27.0	-	Late summer (at 20 m depth)	Smith *et al.* 2003
	0.6	-	-	-	Summer	Mangoni *et al.* 2004
	-	900 (220–1410)	26.0 (23.4–27.8)	-	Summer	Smith & Dunbar 1998
	-	-		101.0 (78.9–133.3)	End spring-early summer	Fabiano *et al.* 1993
	-	-		85.1 (33.4–133.1)	Early summer and summer	Povero *et al.* 2000
	0.43 (0.21)	-	21.18 (2.53)	131.1 (39.80)	Late summer	This study
Ross Sea (TNB) (74°S)						
	2.00 (1.80)	1266 (658)	-	-	Summer	Saggiomo *et al.* 2002
	1.30–1.80	-	16.0–20.0	-	Late summer (at 20 m depth)	Smith *et al.* 2003
	2.70	-	-	-	Summer	Mangoni *et al.* 2004
	-	-	-	445.0 (414.5–522.8)	End spring-early summer	Fabiano *et al.* 1993
	-	-	-	238.4 (88.9–70.8)	Summer	Fabiano *et al.* 1996
	-	-	-	236.8 (157.1–362.9)	Early summer and summer	Povero *et al.* 2000
	1.29 (0.38)	-	13.28 (2.21)	451.1 (137.4)	Late summer	This study

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oceanographic campaigns were focused offshore, to understand the dynamics of the shelf break near Cape Adare (Dinniman *et al.* 2003, Gordon *et al.* 2004) or in the central part of the basin (Smith & Nelson 1985, Fabiano *et al.* 2000b, Povero *et al.* 2000), even with mooring deployment (Ravaioli *et al.* 1999, Langone *et al.* 2000, Collier *et al.* 2000).

The Cape Adare–Cape Hallett area is considered to be characterized by low phytoplanktonic biomass and productivity (Smith & Dunbar 1998, Saggiomo *et al.* 2002, Smith *et al.* 2003, Arrigo & van Dijken 2004, Mangoni *et al.* 2004) and low biogenic sedimentation (Dunbar *et al.* 1985, Langone *et al.* 1998) compared to the southern areas, where fluxes of material are generally twice as great (Collier *et al.* 2000). In TNB, instead, large summer blooms have been reported (Fabiano *et al.* 1996, Innamorati *et al.* 2000, Fonda Umani *et al.* 2002) and these events support large suspension-feeding benthic communities, rich in species and biomass (Albertelli *et al.* 1998, Chiantore *et al.* 1998, 2002, Cattaneo-Vietti *et al.* 1999). At these latitudes, phyto- and zooplankton grow quickly and almost in phase and thus biogenic particles sinking to the bottom are mostly faecal pellets (Fabiano *et al.* 1997, Albertelli *et al.* 1998, Povero *et al.* 2001, Accornero *et al.* 2003).

Another difference between the northern and central sections of the coast of Victoria Land is the stronger hydrodynamism in the Cape Adare area (Picco *et al.* 1999, Budillon *et al.* 2000), whereas the central area usually shows a strong water column stratification in the summer period (Picco *et al.* 2000, Mangoni *et al.* 2004). The different hydrological regimes are also reflected in the annual sea ice cycles. Differences in sea ice conditions at the sampling sites in the productive season (spring–summer) can affect the general productivity. The TNB coastal area is influenced by the presence of a polynya, while the northern areas are not ice free for such a long period (Arrigo & van Dijken 2004), although the total ice-free condition is not so different if we consider the coastal area (< 500 m depth). Differently, the inner part of Cape Hallett usually remains covered by pack ice for longer than the other coastal areas. However, independently of the start of the ice free conditions, the sampling period can be considered the end of the productive season in all the investigated areas.

The results of this study highlighted significant differences in the hydrological and chemical features of the water column from Cape Adare to Terra Nova Bay–Cape Russell. Moreover, latitudinal gradients in the upper layer of the water column were also evident for the organic matter (POC, PON and PPRT), the autotrophic fraction and the bacterial abundance, all of which increased from north to south, while the inorganic nutrients showed the opposite pattern. In the deeper layer, the concentrations were similar in all the areas.

A latitudinal trend was also found in terms of the quality of the organic matter. In fact, the POC:Chl *a* ratio, which estimates the detrital-heterotrophic fraction (Tréguer *et al.* 1990, Fabiano *et al.* 1993), showed higher values (that is a minor autotrophic component) in the upper layer at Cape Adare, but lower values in the deeper layer (POC:Chl *a* 356.9–247.9 for the upper and the deeper layer respectively), although differences are not statistically significant. In Terra Nova Bay, the opposite occurs (POC: Chl *a* values were 351.1 and 847.3 for the upper and the deeper layer respectively, *t*-test $P < 0.05$). The POM appeared to be quite detrital, except for the deeper layer at Cape Adare, where a deep Chl *a* maximum was recorded, although the ratio was higher than those found in the same area in the photic layer earlier in the season (Fabiano *et al.* 1993). According to the literature, similar values were found in this area by Mangoni *et al.* (2004) in weakly stratified waters in the north-west Ross Sea (latitude < 73°S) in deeper layers (depth > 50 m, 0.6 $\mu g\ l^{-1}$) and lower values in the upper ones. The particulate matter was more detrital in the surface layer of TNB, despite a probable second phytoplankton bloom (Chl *a* values > 1$\mu g\ l^{-1}$), as previously recorded in February in this area (Innamorati *et al.* 2000, Grotti *et al.* 2001, Saggiomo *et al.* 2002, Fonda Umani *et al.* 2002, Mangoni *et al.* 2004). This probably reflects previous processes; the end of the first bloom with its higher detrital fraction. Literature data for this area report well-stratified conditions, confining the primary production to the upper layer (Povero *et al.* 2000). Utilizing another index to estimate the detrital fraction of the particulate matter, the POC:PON ratio (Fabiano *et al* 1993), we can observe, instead, a homogeneous trophic quality in the water column (C:N = 7.0, both in the surface and in the deeper layer) at Cape Adare, while in TNB the trophic quality was higher in the upper layer and lower in the deeper one (C:N = 6.2 and 8.6, respectively). In fact, the high bacterial abundance recorded in the upper layer in the TNB–Cape Russell area, although lower than values previously reported for the area (Monticelli *et al.* 2003), can explain the lower trophic value of the sinking particles of the organic matter. These results are consistent with the previous observations of Fabiano *et al.* (1993, 1997), indicating a preferential loss of nitrogen during sedimentation (Tréguer *at al.* 1990, Fabiano *et al.* 1993). In fact, in all the areas investigated, the carbon carbohydrate content was higher in the deeper layer (nearly 40%), in agreement with previous results for the Ross Sea (Fabiano *et al.* 1993, 2000b) and the increase over the upper layer in the central area is significant (*t*-test, $P < 0.001$). Despite the decrease in the labile fraction (PON and PPRT), the protein content remained high (nearly 40%) in the two central areas, even in the deeper layer, where it was considerably higher (*t*-test, $P < 0.05$) than at the northern sites (31.8%).

Our results are in agreement with the hypothesis of major hydrodynamism in the Cape Adare area (Picco *et al.* 1999, 2000, Budillon *et al.* 2000) facilitating a fast sinking of labile and less degraded material (better quality indices and lower bacterial abundances), while in the central area, the stronger stratification of the water column causes a longer permanence of particulate material in the upper layer, but also facilitates the phytoplanktonic bloom and enhances degradation of the particulate material by bacterial activity, although its nutritional value remains high. Furthermore, the primary consumers are more abundant in the highly productive southern area than in the lower latitudes (Zunini-Sertorio *et al*. 1990, 2000, Carli *et al.* 2000).

In the case of the sediments, the northern areas show a lower Chl *a* content, but a slightly higher organic content, while the central area shows the opposite pattern, with values comparable to those already reported for the Terra Nova Bay coastal area (Pusceddu *et al.* 2000). The differences between the areas are not directly related to the sediment grain size or depth. The low values in TNB could be explained by greater utilization by organisms that are abundant in this area (Gambi *et al.* 1997), although distributed very patchily and related to the spatial distribution and availability of the sediment organic matter (Cattaneo-Vietti *et al.* 2000, Pusceddu *et al*. 2000). Previous studies of this area have always reported the high quantity of the organic matter in the sediments in terms of proteins and carbohydrates (Pusceddu *et al.* 2000, Fabiano *et al.* 2000a) and no differentiation with depth, while Fabiano & Danovaro (1998) at 72°S latitude, found lower values (less than half).

The phaeopigment concentration in the sediments changed with latitude, increasing from north to south. High phytopigment values have been recorded in TNB in the past, (Pusceddu *et al.* 2000, Fabiano *et al.* 2000a, Norkko *et al.* 2005), while in the Cape Adare and Cape Hallett areas lower values were found at a comparable depth, but offshore, closer to those recorded in this study, and phaeopigments nearly disappeared (Fabiano & Danovaro 1998).

Phytopigment concentrations were assumed to represent a tracer of the primary organic input of the sediments (Fabiano & Danovaro 1998, Fabiano *et al*. 2000a). The hypothesis of a stronger pelagic-benthic coupling in the TNB and Cape Russell areas was supported by the greater quantity of phaeopigments in the sediments, also in relation to the total autotrophic sedimentary matter (Chl *a*:Phaeo < 1) (Pusceddu *et al.* 2000), partially derived from faecal pellets that were largely abundant in the late summer (Fabiano *et al.* 1997, Fonda Umani *et al.* 2002, Accornero *et al.* 2003, Povero *et al.* 2003).

The PCA analysis of the trophic and environmental parameters in the water column and sediments (Fig. 3, Table VII) highlighted a clear gradient along the first principal component, defining three groups of stations: Cape Adare, Cape Hallett and TNB–Cape Russell.

They differed because of the physical features of the water column, sediment particle size, and the quantity of the potential food supply that increased southwards, although the organic matter degradation also increased.

The overall distribution of the variable loadings in the plot of the first and second principal components indicated that potential sources of food in the productive upper layer (surface POC, Chl *a*) and potential organic matter fluxes (surface nutrient depletion) were strongly related to photosynthetic pigments in the sediments, highlighting the strong pelagic-benthic processes occurring in these areas in this period (Table VII).

To understand how much this latitudinal gradient influences the structure of the benthic communities, we added the biomass percentage data to the previous dataset. The variance explained was lower, although still strongly representative (sum of the two principal components $> 50\%$) (Fig. 4, Table VII) and the three groups were still evident.

Finally, the marine environment of the northern coast of Victoria Land in the late summer showed a latitudinal gradient from Cape Adare to TNB area, in terms of the changing structure of the water column, which affected the organic matter distribution. Cape Adare, showed lower values of organic matter available for the benthic communities, but of good trophic quality; in TNB the particulate organic matter was quantitatively higher, presumably reaching the bottom via faecal pellets, but was more detrital, although its nutritive value was still high, as confirmed by the large quantity of phytopigments in the sediments.

The benthic communities changed with latitudes as well, partially reflecting the environmental and trophic gradient, but also showing a large within-area variability (except for the Cape Adare area), due to a complex array of variables that did not change with latitude (such as bottom morphology and substratum). Thus our study provides further evidence for the importance of a tight pelagic-benthic coupling in structuring high-latitude benthic communities, but also shows the importance of local factors in affecting such coupling and shaping benthic communities.

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