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Lithogenic and biogenic particle deposition in an Antarctic coastal environment (Marian Cove, King George Island): Seasonal patterns from a sediment trap study

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Abstract

Particulate suspended material was recovered over a 23-month period using two sediment traps deployed in shallow water (~30 m deep) off the King Sejong Station located in Marian Cove of King George Island, West Antarctica. Variability in seasonal flux and geochemical characteristics of the sediment particles highlights seasonal patterns of sedimentation of both lithogenic (terrigenous) and biogenic particles in the coastal glaciomarine environment. All components including total mass flux, lithogenic particle flux and biogenic particle flux show distinct seasonal variation, with high recovery rates during the summer and low rates under winter fast ice. The major contributor to total mass flux is the lithogenic component, comprising from 88% during the summer months (about 21 $g\,m^{-2}\,d^{-1}$) up to 97% during the winter season (about 2 $g\,m^{-2}\,d^{-1}$). The lithogenic particle flux depends mainly on the amount of snow-melt (snow accumulation) delivered into the coastal region as well as on the resuspension of sedimentary materials. These fine-grained lithogenic particles are silt-to-clay sized, composed mostly of clay minerals weathered on King George Island. Biogenic particle flux is also seasonal. Winter flux is ~0.2 $g\,m^{-2}\,d^{-1}$, whereas the summer contribution increases more than tenfold, up to 2.6 $g\,m^{-2}\,d^{-1}$. Different biogenic flux between the two summers indicates inter-annual variability to the spring–summer phytoplankton bloom. The maximum of lithogenic particle flux occurs over a short period of time, and follows the peak of biogenic particle flux, which lasts longer. The seasonal warming and sea-ice retreat result in change in seawater nutrient status and subsequent ice-edge phytoplankton production. Meanwhile, the meltwater input to Marian Cove from the coastal drainage in January to February plays a major role in transporting lithogenic particles into the shallow water environment, although the tidal currents may be the main agents of resuspension in this kind of sheltered bay.

Keywords: sediment trap; meltwater; lithogenic particle; phytoplankton; diatom; Marian Cove; Antarctic

1. Introduction

Modern glaciomarine sedimentation patterns in the Antarctic are influenced by a variety of oceanographic and physiographic controls, which are characterized by severe climatic conditions (Griffith and Anderson, 1989; Domack and Ishman, 1993). However, our understanding of the modern sedimentary environment is still limited mainly due to the logistic and practical difficulty of conducting field investigations (Syvitski, 1989). For example, the subglacial environment is by far the most extensive glacial sedimentary environment, but sedimentation beneath the ice sheet is, for obvious reasons, poorly understood. In contrast, a substantial body of literature has been compiled on the subject of fjords and bays, demonstrating the important role of glacial meltwater and sediment-laden iceberg sedimentation (Anderson and Molnia, 1989; Domack and Williams, 1990; Domack and McClennen, 1996; Anderson, 1999).

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The shallow marine environmental setting around the Antarctic Peninsula is highly sensitive to seasonal contrasts determined by the climatic gradients in both temperature and precipitation. During the winter, sea-ice formation cuts off the transport of sediments from the nearby terrestrial environment (Domack and Ishman, 1993). In contrast, in the spring and summer, large discharges of meltwater from glacier termini lead to the widespread dispersal of terrigenous materials. Thus, the volume of meltwater is considered to be a major factor controlling the sedimentation, transportation and deposition of terrestrial debris (Domack and McClennen, 1996; Yoon et al., 1998; Khim et al., 2001). At the same time, biological activity in the shallow marine environment tends to start during the spring, resulting in the contribution of abundant biological remnants to the bottom sediments (Walker, 2005). Therefore, the primary modes of sediment deposition include the settling of fine-grained terrigenous particulate matter mainly from sediment-laden ice calved from the continental glaciers and meltwater from the same source, as well as biogenic material from suspension. However, because of the difficulties involved in conducting field study in the shallow polar marine setting, it is challenging to investigate seasonal patterns of sedimentation (Berkman et al., 1986; Nedwell et al., 1993; Cripps and Clarke, 1998; Isla et al., 2001).

Time-series sediment trap moorings have been the best way to detect the seasonal differences of the downward particle fluxes in the open Antarctic Ocean (Fischer et al., 1988; Wefer et al., 1988; Wefer and Fischer, 1991; Dunbar et al., 1998; Honjo et al., 2000; Anadón et al., 2002; Masqué et al., 2002; Palanques et al., 2002a,b). These studies have furthered our understanding of elemental cycling in terms of vertical flux of particulate matter, as well as lateral transport of sediment particles induced by resuspension and winnowing. Most sediment trap mooring deployments have been focused on the deep oceans, with a goal of addressing global and regional oceanographic and climatic changes (e.g., Anadón et al., 2002; Palanques et al., 2002a,b). A few moored sediment trap studies have been conducted in the shallow marine environment (e.g., Nedwell et al., 1993; Cripps and Clarke, 1998; Isla et al., 2001), but due to severe weather conditions, access to the shallow marine environment in the Antarctic is limited, hence the sediment trap studies have been only moderately successful.

In Maxwell Bay, West Antarctica (Fig. 1), the tidewater glaciers are heavily crevassed; meltwater streams are common and typically drain into small bays and coves (Klöser et al., 1994). Surface plumes of sediment-laden meltwater have been observed adjacent to nearly all of the tidewater glaciers of the small bays. These sheltered coves are covered by sea ice for several months of the year; this sea ice breaks up very quickly in the spring and the area is ice-free throughout the summer. Summer is characterized by a dense phytoplankton bloom

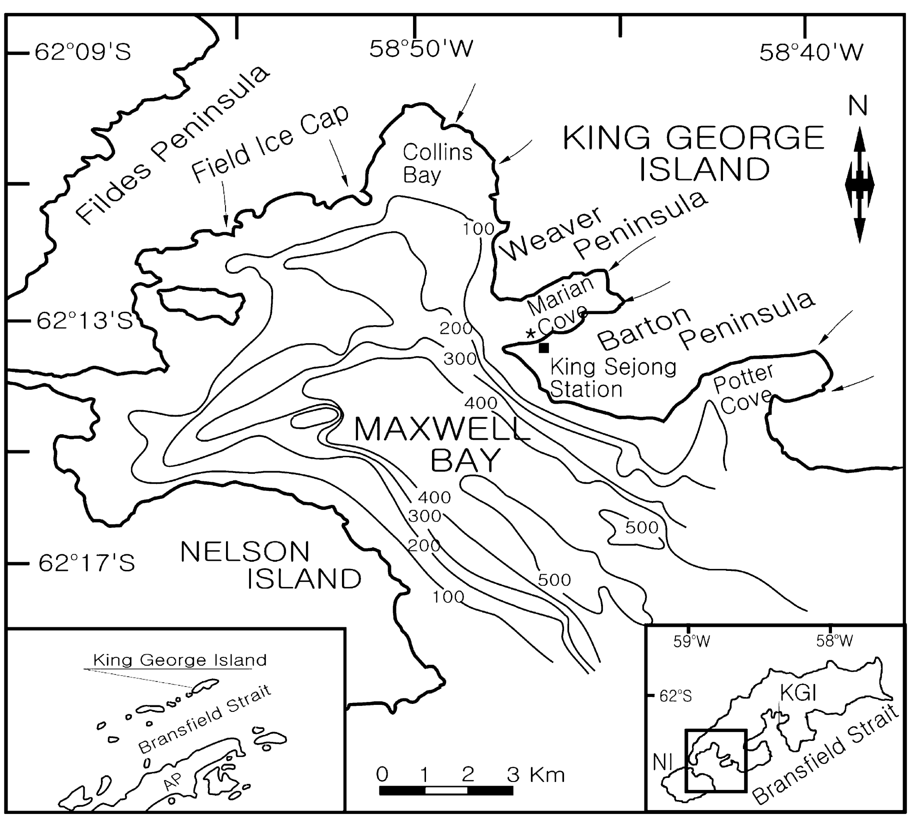

Fig. 1. Map showing Marian Cove surrounded by Weaver and Barton Peninsulas in King George Island in South Shetlands Islands (Antarctica). The sediment traps were deployed at 30-m deep bottom off King Sejong Station. Asterisk indicates the location for the sediment trap. Arrows represent the present direction of glacier movement. The bathymetry is in meters. AP: Antarctic Peninsula, NI: Nelson Island, KGI: King George Island.

usually of short duration, and a longer but less intense nanoplankton (predominantly flagellates) bloom (Ahn et al., 1997; Kang et al., 1997b). In this study, we deployed sediment traps in the shallow marine setting for the purpose of elucidating the seasonal contrast of coastal glaciomarine sedimentation patterns, in particular timing of both lithogenic and biogenic particle fluxes in Marian Cove, Maxwell Bay, West Antarctica. These data will improve both our understanding of modern marine processes and our interpretation of past conditions from sedimentary records.

2. Study area and environmental setting

King George Island is largest among the South Shetland Islands, located west of the Antarctic Peninsula (Fig. 1). Maxwell Bay (14 km long and 6–14 km wide) is one of the deep and U-shaped fjords along the southern margin of island. At present, it is surrounded by ice cliffs creeping from the low-profile ice cap of Fildes Peninsula and Nelson Island. Starting in late October, the sea ice begins to break up rapidly and numerous icebergs are scattered in Maxwell Bay. The surface waters of Maxwell Bay freeze regularly in winter, from late July to mid September. During the summer, surface layer of warmer (1.0 to 0 °C) and less saline (33.9 to 34.0‰) overlies the colder (0 to −0.3 °C) and more saline (34.0 to 34.5‰) subsurface water mass in Maxwell Bay (Khim et al., 1997).

Several tributary embayments are developed in Maxwell Bay, including Marian Cove (3.5 km long and 1.2 km wide) and Potter Cove in the northeast and Collins Bay in the north (Fig. 1). Small valley glaciers draining into Marian Cove deliver icebergs and large volumes of turbid meltwater during the summer months (Klöser et al., 1994; Yoon et al., 1998; Yoo et al., 2000). Most ice-rafted debris originates from icebergs calved off the edges of glaciers, whereas fine-grained particles are discharged by the melting waters during the summer. The cove becomes completely ice-free during the summer (November to February), leading to increased primary biological productivity. The bottom sediments in Marian Cove are silty sand and mud including ice-rafted debris with a development of broad gravel beach.

King Sejong Station is located on the Barton Peninsula, where atmospheric and oceanographic properties have been measured daily since 1988 (Fig. 1; MOMAF, 2000). Fig. 2 illustrates atmospheric conditions, including air temperature, wind speed and snow accumulation during the period the sediment trap investigation was conducted. Seawater properties such as temperature, salinity and chlorophyll *a* concentration have been also measured at the nearshore station in front of the pier of King Sejong Station, Marian Cove (Fig. 2; MOMAF, 2000). Air temperature fluctuated seasonally (Fig. 2a), showing relatively stable summer and cold winter temperature. The average air temperature (−1.2 °C) in 1998 was lower than that in 1999 (−0.7 °C). Wind speed showed no seasonal pattern and the average speed was 8.8 $m\,s^{-1}$ with NNW direction (Fig. 2b). The number of storm days (wind > 13.5 $m\,s^{-1}$) occurring in winter was not large. Snow accumulation is clearly seasonal. The maximum accumulation rate was 63.0 $cm\,d^{-1}$, during winter 1998 (Fig. 2c). Snow accumulation was higher in 1998 than in 1999, corresponding to the winter air temperatures. In Marian Cove, sea-ice formation during 1998 (49 days, continued to form from 20 August to 8 October) was characterized by longer period than in 1999 (21 days, from 26 August to 15 September), which seems to be in agreement with the winter air temperature (Fig. 2c).

During the period from February 1998 to January 2000, seawater temperature fluctuated seasonally (Fig. 2d), similar to that of Maxwell Bay (Khim et al., 1997). Salinity also showed seasonal variation (Fig. 2e). The winter salinity in 1998 was higher than that in 1999, coinciding with the air temperature pattern (Fig. 2a). The lower summer salinity in 1999 may be attributed to greater volume of meltwater discharged into the cove from the thick snow accumulated during 1998. Chrolophyll *a* concentration was 0.1 to 12.2 $\mu g\,L^{-1}$ with an average of 0.5 $\mu g\,L^{-1}$ (Fig. 2f). According to Kang et al. (1997b), the average concentration of chlorophyll *a* was 1.4 $\mu g\,L^{-1}$ in 1996, which is higher than that during the study period. High chlorophyll *a* was measured during summer due to increased biological activity.

3. Materials and methods

Two sediment traps were deployed in Marian Cove from February 1998 to January 2000. In general, trap collection was done on a monthly basis, except from August through September 1998 due to the thick sea-ice condition that prevented monthly servicing (Table 1). In November 1999, a 15-day collection interval was used in order to detect the austral spring bloom. Sediment traps were deployed at 30 m depth and approximately 150 m from the pier of King Sejong Station (Fig. 1). The sediment trap is composed of three parts; the main trap body consisting of 7-cm wide and 100-cm long PVC chamber, the removable 2 L PE sample bottle, and a stainless steel tripod for holding the trap. Deployment and retrieval of the sediment traps were conducted manually by a scuba diver. No preservatives were used to keep the settling particles, presumably resulting in an underestimate of downward flux, due to sediment microbial decomposition of the trap contents (Walker, 2005). Immediately after the bottles were retrieved, they were frozen at −20 °C prior to analysis in the laboratory.

The freeze-dried particles were ground for further analysis. Total carbon (TC) and total nitrogen (TN) contents were measured using a Carlo Erba NA-1500 Elemental Analyzer. After removing $CaCO_3$ by 8% H_2SO_3, total organic carbon (TOC) content was obtained through the same procedure (Verardo et al., 1990; King et al., 1998). Total inorganic carbon (TIC) content was determined using the difference between TC and TOC contents, from which $CaCO_3$ is calculated as weight percentage multiplying TIC content by 8.333.

Biogenic silica (Si_{BIO}) content was analyzed by wet alkaline extraction modified from Mortlock and Froelich (1989) and Müller and Schneider (1993). Duplicate measurements were conducted on each sample. The relative error of Si_{BIO} content in sediment samples was lower than 2%. Opal content

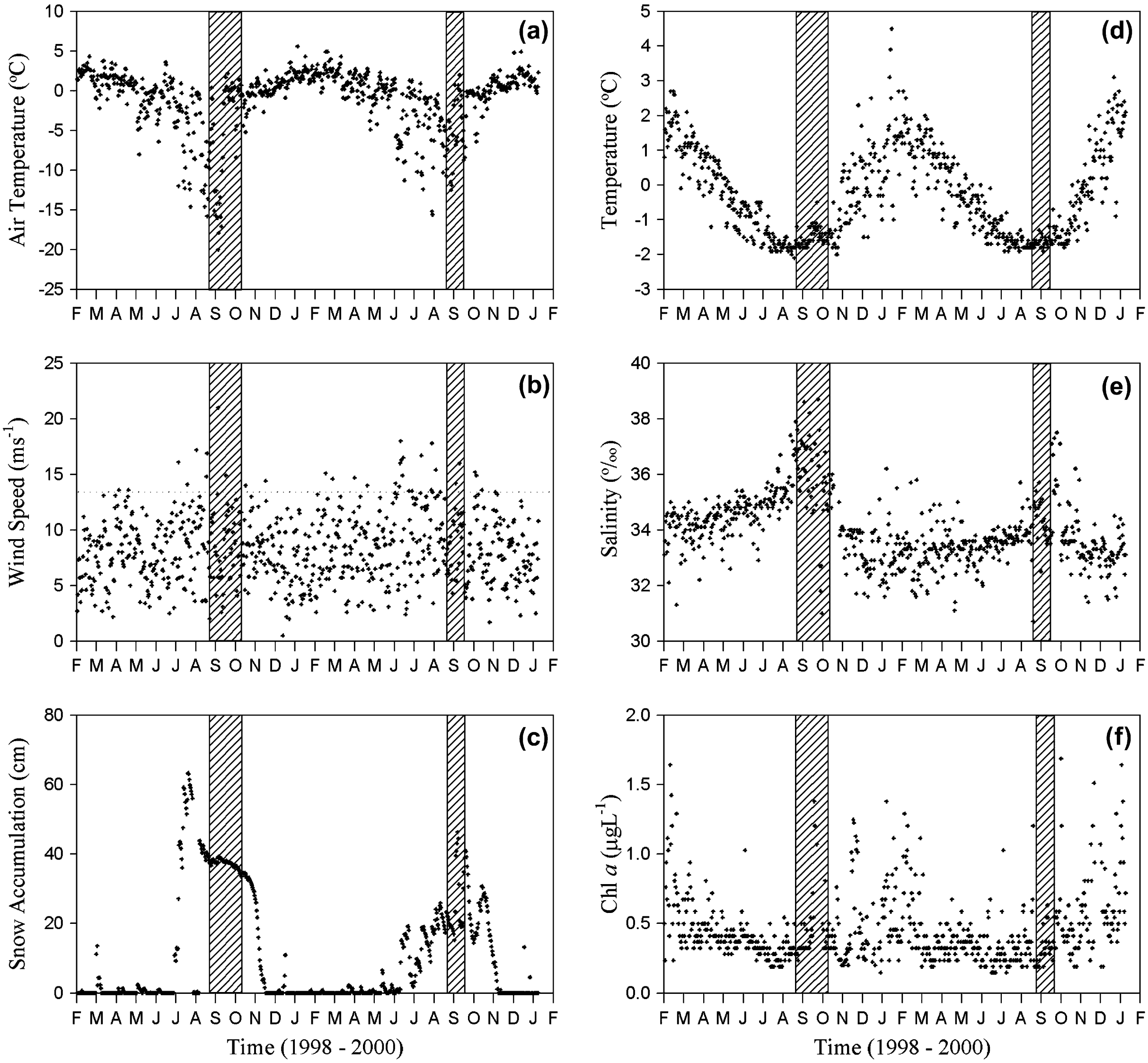

Fig. 2. Temporal variation of the atmospheric and coastal water conditions during the sediment trap deployment (1998−2000). Weather station is located at the King Sejong Station in Barton Peninsula. The seawater sample was collected daily at the nearshore station in front of the pier of King Sejong Station in Barton Peninsula. (a) Air temperature (°C), (b) wind speed (m s^{-1}), the horizontal dotted line represents the minimum speed of storm event, (c) snow accumulation (cm), (d) seawater temperature (°C), (e) salinity (‰), (f) chlorophyll *a* concentration (μg L^{-1}) (modified after MOMAF, 2000). The hatched area represents the duration of sea-ice coverage. In 1998, sea-ice condition lasted for 49 days, continued to form from 20 August to 8 October, whereas 21 days were counted to show sea-ice formation from 26 August to 15 September in 1999.

is calculated by multiplying Si_{BIO} content by 2.4. Sediment samples for stable carbon and nitrogen isotope analyses were measured at the University of California, Davis. Carbon and nitrogen isotope ratios in sediment organic matter are expressed in conventional delta notation, which is the per mil deviation from the Vienna Pee Dee Belemnite (V-PDB) and atmospheric nitrogen. Precision for carbon and nitrogen isotopes is about ±0.1‰ and ±0.2‰, respectively.

For the mineralogical identification of sampling particles, the unoriented mounts of powdered slides were prepared for standard X-ray diffraction analysis, from 3° to 60° at 2°2*θ*/min on an X-ray diffractometer using Ni filtered Cu−K_α radiation, equipped with an automated divergent slit. The clay minerals were identified by the basal reflections using procedures outlined elsewhere (Brindley and Brown, 1980; Moore and Reynolds, 1989).

There are many practical difficulties associated with the deployment of sediment traps in the shallow-water Antarctic marine environment, including damage by ice, contamination by resuspended bottom sediments and artifacts introduced by horizontal transport into situating traps within the euphotic zone (Nedwell et al., 1993; Cripps and Clarke, 1998; Walker, 2005). In the shallow marine environment, the set-up position of sediment trap is very important for the efficiency of trap, depending on the site of summer phytoplankton bloom and the local influx from the coastal areas where efficiency depends on the turbulence. Consequently, two sediment traps were deployed within 10 m from one another. Some of

Table 1
Durations and numbers of sediment trap deployed in Marian Cove during 1998 to 2000 period

Bottle no.	Trap deployed (yr/mon/day)	Trap retrieved (yr/mon/day)	Duration (days)	No. of traps deployed
1	98/02/28	98/03/30	30	2
2	98/03/30	98/04/29	30	1
3	98/04/29	98/05/29	30	2
4	98/05/29	98/07/02	34	2
5	98/07/02	98/07/30	28	2
6	98/07/30	98/10/09	71	2
7	98/10/09	98/11/09	31	2
8	98/11/09	98/12/09	30	2
9	98/12/09	99/01/11	33	2
10	99/01/11	99/02/09	29	2
11	99/02/09	99/03/08	27	1
12	99/03/08	99/04/08	31	2
13	99/04/08	99/05/10	32	2
14	99/05/10	99/06/10	31	2
15	99/06/10	99/07/09	29	2
16	99/07/09	99/08/12	34	2
17	99/08/12	99/09/16	35	2
18	99/09/16	99/10/27	41	2
19	99/10/27	99/11/17	21	2
20	99/11/17	99/12/03	16	2
21	99/12/03	99/12/31	28	2
22	99/12/31	00/01/22	22	2

deployments were not retrieved safely, thus, some months showed a single datum (Figs. 3 and 4). In our dual sediment trap data, the comparison shows the minimal deviation during winter, in contrast, greater variability is observed in the summer data. This variability may be due to patchy phytoplankton blooming of micro-sized or nano-sized organisms, different vertical settling, meltwater influx controlled by wind speed and other atmospheric conditions.

4. Results

Total mass flux is calculated, based on the dry weight of trapped samples, duration of deployment, and the surface area of the trap, assuming that it consists only of the lithogenic and biogenic component fluxes. The relationship among them is taken from Fischer and Wefer (1996) as follows: total mass flux = lithogenic particle flux + biogenic particle flux, the latter of which is expressed as a total of opal flux, calcium carbonate ($CaCO_3$) flux and twice that of total organic carbon (TOC) flux.

Total mass flux shows distinct seasonal variability from 2.27 $g\,m^{-2}\,d^{-1}$ in winter to 23.69 $g\,m^{-2}\,d^{-1}$ in summer (Fig. 3a). It decreases from April 1998, reaching the minimum in August and September 1998, then increases to the maximum in February 1999. This seasonal variation follows the same trend in the second year, in spite of inter-annual variation of total mass flux. The spring and summer fluxes are higher than the winter and fall fluxes. Maximum flux occurs in January and February during both years.

Lithogenic particle flux is obtained from the mass difference between the total mass flux and measured biogenic particle flux. The seasonal variation of lithogenic particle flux is almost same as that of total mass flux (Fig. 3b). The winter season is characterized by a minimum value of about 2.0 $g\,m^{-2}\,d^{-1}$ that comprises up to 97% of total mass flux. In contrast, the maximum values are obtained in the summer period with about 21.0 $g\,m^{-2}\,d^{-1}$ that forms about 88% of total mass flux. The average weight is 9.3 $g\,m^{-2}\,d^{-1}$, and is an average 90% of total mass flux. The lithogenic particle flux is higher in 1999 than in 1998. Maximum peak flux is observed in January and February, the same as the total mass flux.

Variation of biogenic particle flux is also seasonal (Fig. 3c). During the winter, flux remains as low as about 0.2 $g\,m^{-2}\,d^{-1}$, whereas the summer flux increases more than tenfold up to about 2.6 $g\,m^{-2}\,d^{-1}$. However, an even more striking difference is the relative timing of biogenic versus lithogenic flux increases and maxima flux. The increase of lithogenic particle flux starts in December to January, reaching the maximum in January to February, whereas the biogenic particle flux increases in early October to November, reaching the maximum peak in November and December.

Because opal content is calculated directly from the biogenic silica (Si_{BIO}) content, their variations are the same (Fig. 4a and b). Si_{BIO} content is less than 2% during most of year, but contents up to 12% are measured from October to December (Fig. 4a). Summer Si_{BIO} content is higher in 1998, but winter Si_{BIO} content is higher in 1999. Thus, opal flux shows the seasonal variation such as minimum (62.7 $mg\,Si\,m^{-2}\,d^{-1}$) during the winter and maximum (400 to 1600 $mg\,Si\,m^{-2}\,d^{-1}$) during the summer (Fig. 3d), reflecting the magnitude of the phytoplankton blooms and degree of sea-ice coverage. The sharp increase of opal flux may correspond to the complete disappearance of sea ice.

The $CaCO_3$ content is calculated from total inorganic carbon (TIC) content. The TIC comprises very insignificant portion of flux (<0.6% during the deployment), which is less than 30% of total carbon (Fig. 4c). In spite of its small flux, $CaCO_3$ flux varies seasonally, being high during February to March and low during August and September. The pattern of $CaCO_3$ flux is more similar to lithogenic particle flux rather than biogenic particle flux (Fig. 3e).

TOC and TN contents, both biogenic indicators, show similar variation (Fig. 4d and e). TOC content is usually 1% and increases up to 5% during September to November, when environmental conditions are favorable for phytoplankton bloom (Fig. 4d). TN content is normally <0.2% and increases to >0.4% during the summer (Fig. 4e). Like TOC content, TN content was higher in 1998 than in 1999. The TOC/TN ratio is generally higher than Redfield ratio values in 1998 (Fig. 4f). TOC flux fluctuated between about 48 and 240 $mg\,C\,m^{-2}\,d^{-1}$ except for a sample of >400 $mg\,C\,m^{-2}\,d^{-1}$. In general, flux was low during fall and winter and high during spring and summer (Fig. 3f). While flux increases rapidly from September to October, decrease through the summer is more gradual. Most notable is the very high flux in November 1999, compared to the previous year. The average TOC flux is 115.4 $mg\,C\,m^{-2}\,d^{-1}$, which is orders of magnitude higher than fluxes in the open ocean (cf., Nedwell et al., 1993; Cripps and Clarke, 1998; Isla et al., 2001).

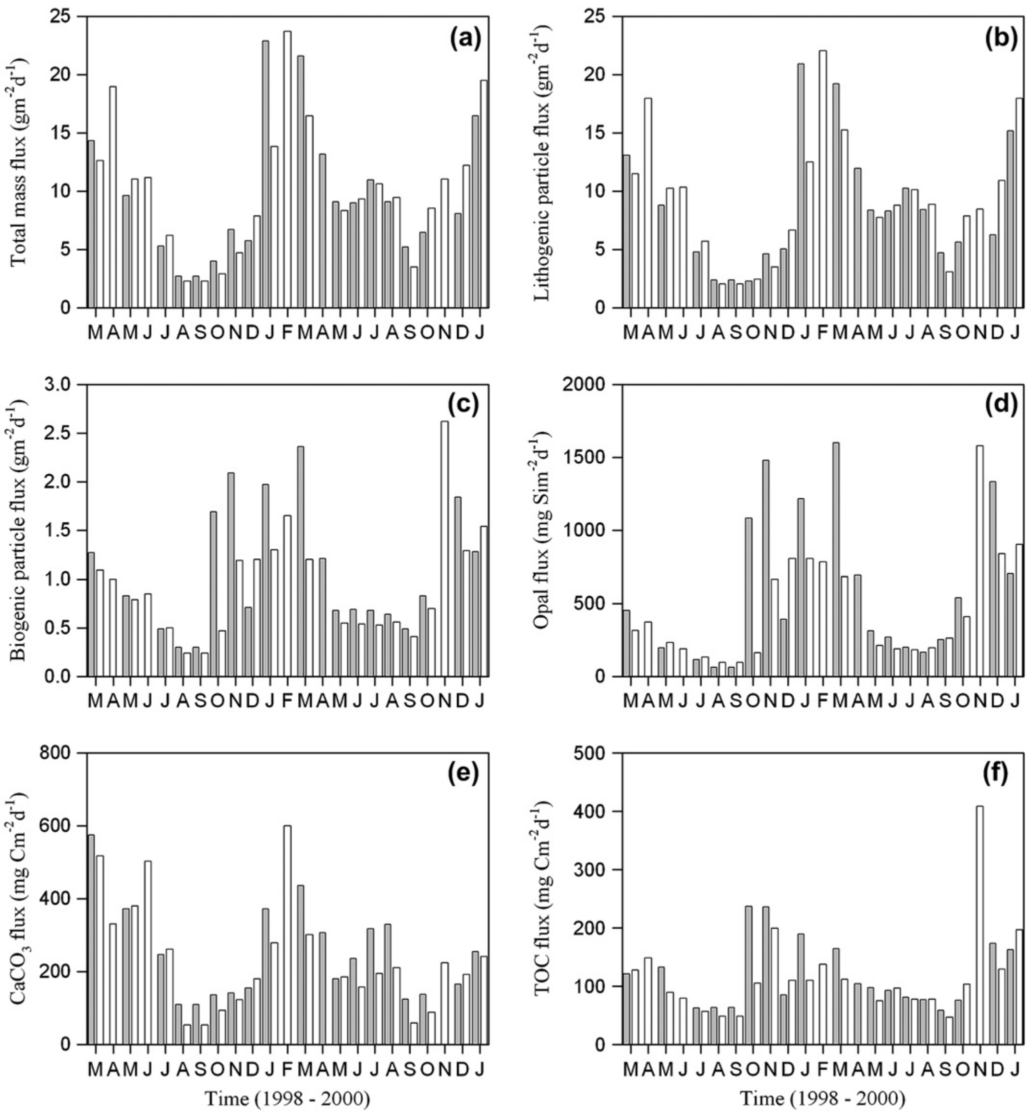

Fig. 3. Temporal variation of monthly measured fluxes of two sediment traps. (a) Total mass flux (g m^{-2} d^{-1}), (b) lithogenic particle flux (g m^{-2} d^{-1}), (c) biogenic particle flux (g m^{-2} d^{-1}), (d) opal flux (mg Si m^{-2} d^{-1}), (e) $CaCO_3$ flux (mg C m^{-2} d^{-1}), (f) total organic carbon (TOC) flux (mg C m^{-2} d^{-1}). Two flux values (one as hatched bar and another as blank bar) are compared as a representative of month, except for several months to show a single value.

The $\delta^{13}C$ values of particulate organic carbon clearly exhibit seasonal variation (Fig. 4g). In general, $\delta^{13}C$ values as low as −26.3‰ occur during the winter whereas high $\delta^{13}C$ values, up to −20.2‰, characterize the summer bloom. The summer $\delta^{13}C$ peak is more obvious in 1998 than in 1999 and winter $\delta^{13}C$ values are higher in 1999 than in 1998. In contrast to $\delta^{13}C$ values, the $\delta^{15}N$ values of organic nitrogen are seemingly scattered (Fig. 4h). However, careful observation illustrates that the $\delta^{15}N$ values are higher (2.5 to 5.5‰) in winter than in summer (0.5 to 4.0‰). In general, during the warm periods, the $\delta^{13}C$ values become high and the $\delta^{15}N$ values decrease.

5. Discussion

The variability of particle fluxes in the Southern Ocean has been explained by the spring sea-ice thaw processes rather than the availability of larger areas of uncovered open seas (Fischer et al., 1988; Wefer et al., 1988; Dunbar et al., 1998; Anadón et al., 2002; Masqué et al., 2002). The main feature of seasonal fluctuation in the open ocean is the abrupt increase in particle flux following the disappearance of sea-ice cover, and the sudden and near-complete termination of particle sedimentation while the ocean is still open (Wefer et al., 1988; Holm-Hansen and Mitchell, 1991; Honjo et al., 2000; Palanques et al., 2002a,b). In shallow waters, the annual advance and retreat of coastal sea ice appear to control the initiation and termination of phytoplankton blooms (Nedwell et al., 1993; Murphy et al., 1995; Cripps and Clarke, 1998; Walker, 2005). In addition to the biogenic component, resuspended or winnowed particles in shallow marine environments are an important fraction along with the transported terrigenous particulates from sediment-laden ice and meltwater (Berkman et al., 1986; Domack and McClennen, 1996; Isla et al., 2001).

Total mass flux in Marian Cove shows a clear seasonal pattern; high in summer and low in winter despite inter-annual

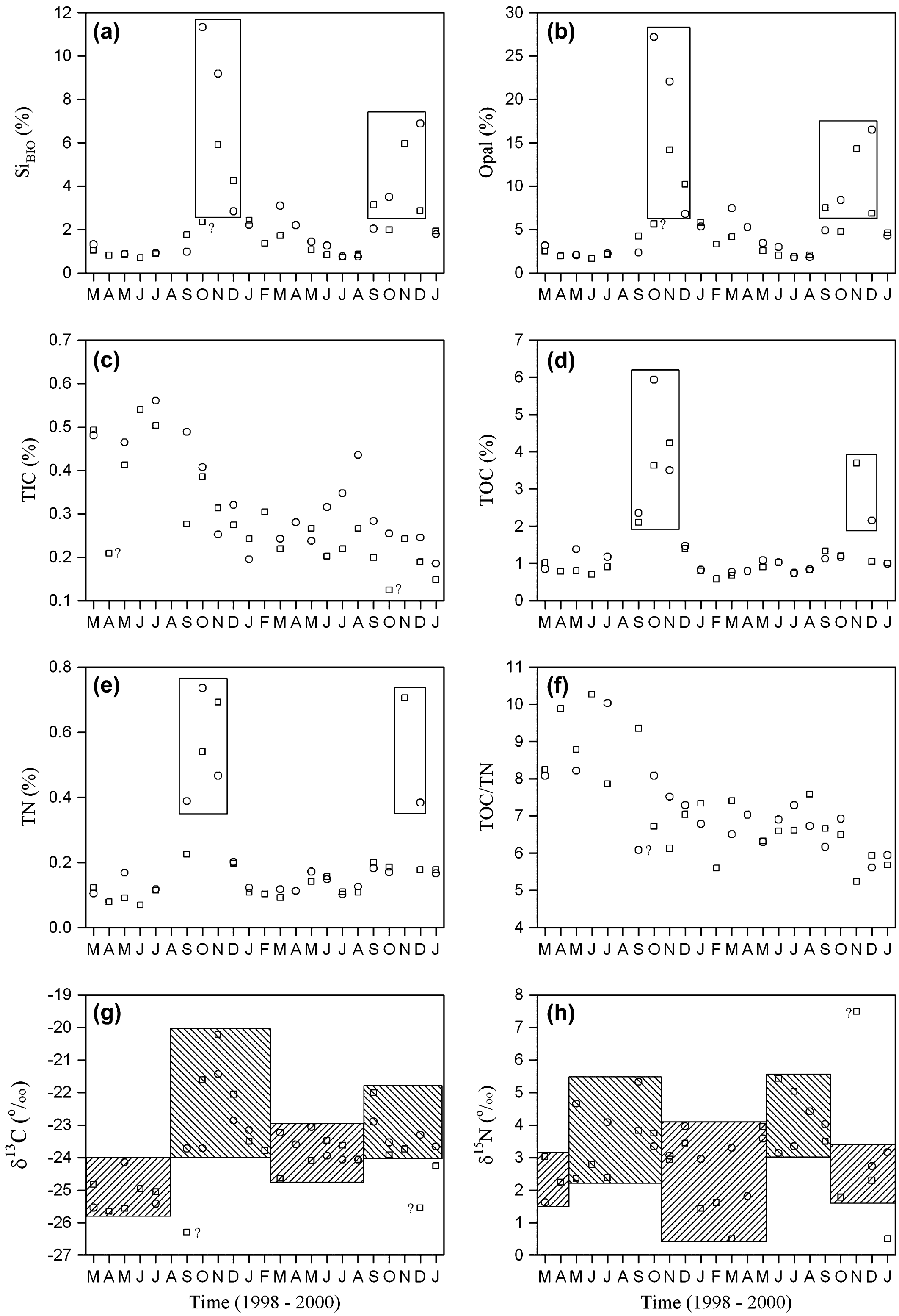

Fig. 4. Temporal variation of monthly-measured geochemical contents of two (open circle and rectangle) sediment traps. (a) Biogenic silica (Si_{BIO}) content (%), (b) opal content (%), (c) total inorganic carbon (TIC) content (%), (d) total organic carbon (TOC) content (%), (e) total nitrogen (TN) content (%), (f) TOC/TN (C/N) ratio, (g) $\delta^{13}C$ values of organic matter (‰), (h) $\delta^{15}N$ values of organic matter (‰). Inset box in Si_{BIO}, opal, TOC and TN represents the time and duration of maximum values of two years. The hatched boxes in $\delta^{13}C$ and $\delta^{15}N$ values are arbitrarily defined to divide the summer and winter trend.

variability (Fig. 3a). Lithogenic particle flux follows the seasonal variation of total mass flux (Fig. 3b). The peak of lithogenic particle flux lasts from January through March. In general, the lithogenic particle flux may depend not only on the amounts of meltwater delivered from the coastal region, but also on the relationship with both wind speed and snow accumulation (i.e., snow-melt). In our study area, lithogenic particle flux comprises about 90% of total flux; 88% in summer and 97% in winter. In contrast, in the open ocean, such as Weddell Sea, the fraction of lithogenic flux is as low as 1%, because ice-rafting is the only transport agent from the continental area (Fischer et al., 1988; Wefer et al., 1988; Anadón et al., 2002; Palanques et al., 2002a,b). In the Ross Sea, the lithogenic fraction increases up to 20% in the ice-edge area close to the continent during spring and summer (Dunbar et al., 1998). Wefer et al. (1988) reported that the Bransfield Strait is characterized by >50% lithogenic particle fraction. Large quantities of lithogenic particle fractions from sediment trap studies have been reported elsewhere, for example, Signy Island (Clarke and Leakey, 1996), McMurdo Sound (Berkman et al., 1986) and Livingston Island (Isla et al., 2001), all of which were compared to our study.

Fig. 5 provides an important information to demonstrate the seasonal variation of the amount of lithogenic particles in Marian Cove. The relationship between lithogenic particle flux and snow accumulation measured at King Sejong Station during the trap deployment period seems to be moderately correlated ($r^2 = 0.57$; Fig. 5a). The lithogenic particle flux is generally controlled by the amount of meltwater-induced influx to the shallow marine environment. The result of this study is consistent with previous works (Klöser et al., 1994; Yoon et al., 1998; Yoo et al., 2000). Thick snow accumulation during the previous winter (Fig. 2a) when air temperature and seawater temperature were low is a pre-requisite to supply the increased amount of snow-meltwater into the coastal waters. Snow accumulation was higher in 1998 than in 1999, resulting in more lithogenic component during spring–summer next year (Fig. 2c). The low salinity in the summer of 1999 corresponds to greater discharge of snow and glacial meltwater from King George Island during that year. In addition, the duration of sea-ice formation was longer in 1998 than in 1999 (Fig. 2c). The extended duration limited the particle influx into the water during the winter, which corresponds to the low lithogenic flux during the winter in 1998.

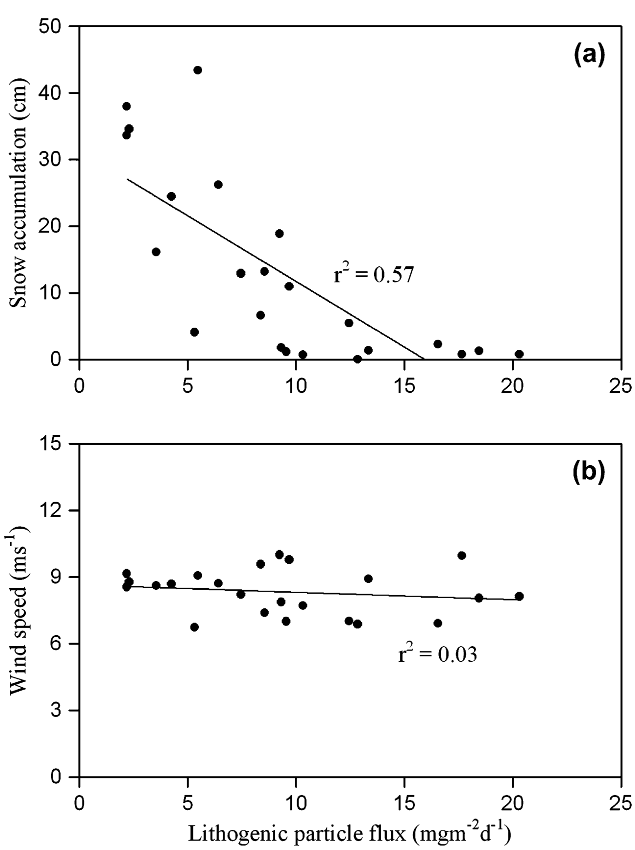

Fig. 5. (a) Relationship between lithogenic particle flux ($g\,m^{-2}\,d^{-1}$) and snow accumulation (cm) around King Sejong Station during the study period. (b) Relationship between lithogenic particle flux ($g\,m^{-2}\,d^{-1}$) and wind speed ($m\,s^{-1}$) measured at King Sejong Station during the study period.

Sediment trap studies in shallow marine waters suggest that sediment resuspension may be another key process that contributes lithogenic particles to the nearshore environment. Resuspension is particularly important in the sublittoral area during the austral winter, increasing the occurrence of sediment particles in the water column. Berkman et al. (1986) demonstrated that resuspended sediments in the vicinity of McMurdo Station (East Antarctica) contained viable algal material throughout the winter darkness period. In Maxwell Bay and Marian Cove, an important source of suspended particulate matter also seemed to be resuspension of benthic material throughout a year cycle (Kang et al., 1997a). In these bays, daily tidal currents regularly resuspend benthic diatoms which constitute a food source for other benthic communities (Ahn et al., 1997). The correlation between the lithogenic particle flux and wind speed is not good ($r^2 = 0.03$; Fig. 5b), suggesting that wind-induced transport and resuspension are unimportant processes in terms of supplying lithogenic particles into coastal waters. However, in a sheltered bay like Marian Cove, where only a few wind directions create resuspension, tidal currents may be the main agent of resuspension. From our sediment trap samples, it is difficult to determine the amount of resuspended lithogenic particles. Based on the moderate relationship between lithogenic particle flux and snow accumulation (i.e., amount of meltwater), resuspension is likely a secondary contribution to our sediment trap, despite the lack of correlation between the lithogenic particle flux and wind speed (Fig. 5b).

Yoon et al. (1998) reported that the suspended lithogenic particulates in Marian Cove are composed dominantly of silt-to-clay sized grains based on SEM analysis. Although the extent of coastal glacier retreat showed the inter-annual variability during the last 40 years, suspended particulate matter characteristics may not have changed rapidly, reflecting that hydrodynamic conditions in Marian Cove remain unchanged. The bulk sediments recovered during the winter period are almost entirely lithogenic grains with little to no biogenic contributor. In both sediment traps, these lithogenic particles are mainly aluminosilicates, based on the chemical analyses of bulk sediments (Shim et al., 2005), as confirmed by XRD analysis (Fig. 6). Quartz, feldspar and other major clay minerals are identified. The clay minerals are very similar to those in the Maxwell Bay and Bransfield Strait (Yoon et al., 1997).

In the open ocean, biogenic particulate material is provided mainly by primary production in surface waters, and the most important biological process leading to its biochemical modification is grazing (Abelmann and Gersonde, 1991; Holm-Hansen and Mitchell, 1991; Honjo et al., 2000; Palanques et al., 2002b). Conversely, the relatively short residence time of particulate matter in the water column in the shallow near-shore environment suggests that much of the sinking materials may reach the sediment bottom unaltered. Biological activity is dependent on the season in the shallow marine environment, being active in summer and inactive in winter. In spring, the seawater temperature increases and maintains water column stability. In this setting, abundant nutrients result in an ice-edge algal bloom similar to open water conditions. In our study, biogenic particle flux is relatively small (max. 12% in summer) compared to the lithogenic particle flux (Fig. 4c). In contrast, in the Bransfield Strait, biogenic particle flux comprises up to 70% of total mass flux (Wefer et al., 1988). Micro-sized phytoplankton (*Fragilaria striatula*, *Licmophora belgicae*, *Achnanathes groenlandica*) blooms during the spring to summer, while nano-sized phytoplankton (*Phaeocystis antarctica*, *Navicula glaciei*, *Navicula perminuta*) continues to bloom during the warm period in Marian Cove (Kang et al., 2002). Two prominent features can be observed from the pattern of biogenic particle flux. Firstly, it is noticeably seasonal, resulting from intensive phytoplankton blooms during the summer (Fig. 3c). Secondly, the highest flux of biogenic particle occurs in advance of that of lithogenic particle (Fig. 3b).

In the pelagic ocean such as Weddell Sea and Ross Sea, seasonal primary production varies as a result of the solar cycle and the large-scale oscillation of the ice-edge melting (Fischer et al., 1988; Wefer and Fischer, 1991; Dunbar et al., 1998; Anadón et al., 2002). Although annual particle flux shows extreme variability, phytoplankton production partly seeded by diatoms results in the maximum fluxes of siliceous biogenic particles occurring during the periods of highest total flux (Fig. 3c). In our sediment trap study, we clearly observe that the deposition of biogenic particles is obviously seasonal,

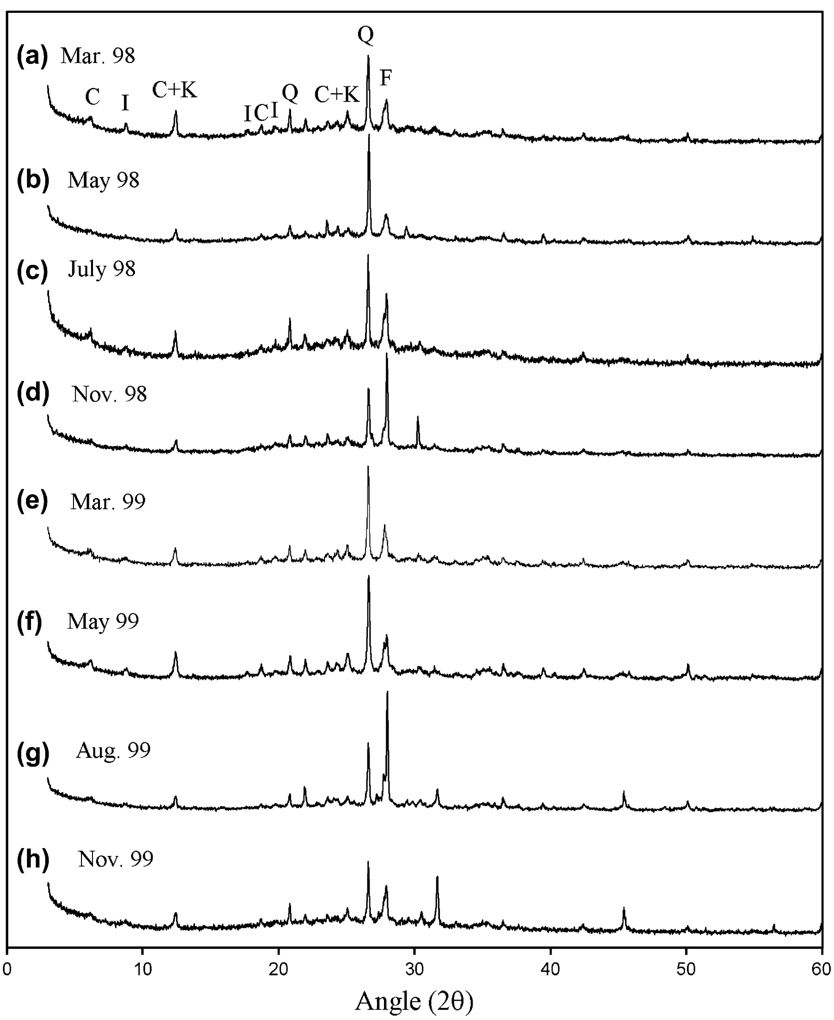

Fig. 6. X-ray diffractograms showing mineralogy of lithogenic particles in Marian Cove. C: chlorite, I: illite, K: kaolinite, Q: quartz, F: feldspar, P: pyroxene.

although the biogenic particle flux is normally less than 7% of total and increases up to 10% during spring to summer by biological activity (Fig. 3c). The biogenic particle flux assumes the total of opal, calcium carbonate and total organic carbon flux. However, while the opal and total organic carbon fluxes synchronize the biogenic particle flux, $CaCO_3$ flux follows opal and TOC (Fig. 4e), suggesting that carbonate production happens after diatom blooming in the study area.

Stable carbon isotope data have been used widely to trace sources of particulate organic matter and its biogeochemical transformation through the water column (e.g., Altabet, 1996). Given the short downward transit time of particles in Marian Cove, we suggest that the primary signal dominates. In case of our small-scale survey, it can be assumed that the CO_2 level and sea surface temperature are not critical factors that affect isotopic fractionation (Rau et al., 1997). The $\delta^{13}C$ values of the organic matter show a seasonal variation with high $\delta^{13}C$ value during summer and low $\delta^{13}C$ values during winter (Fig. 4g). The high $\delta^{13}C$ values occurring during the summer season are attributed to phytoplankton blooms dominated by mostly diatoms (O'Leary, 1981). The low $\delta^{13}C$ values of the sediment organic matter trapped in Marian Cove during the winter may be attributed to the resuspended particles, a minor fraction of terrestrially derived carbon, other non-biogenic components, corresponding to those reported by Minagawa (1995).

Most isotopic variations in marine organic matter first consist in a depletion of ^{15}N that is imparted from inorganic precursors (i.e., primary production; Altabet, 1988). Then, a stepwise enrichment of ^{15}N occurs in particles along the food chain (Minagawa and Wada, 1984). The $\delta^{15}N$ values of sediment trap particles in our study provide further evidence of the seasonality of biogenic particle flux (Fig. 4h). In contrast to the carbon isotopic composition, the $\delta^{15}N$ values are lowest during the phytoplankton bloom. Although the magnitude of the phytoplankton bloom and species diversity depend largely on the extent of sea-ice coverage, Kang et al. (2002) reported that microplanktonic diatoms contribute >50% of total phytoplankton carbon. In addition, Ahn et al. (1997) emphasized that resuspended benthic diatoms are an important biomass source in the nearshore environment, although epiphytic forms are dominant. According to Wada et al. (1987), Antarctic settling organic matter is characterized by low $\delta^{15}N$ value, at around 1‰. Such low isotopic values are explained by intense and continual input of high nitrate concentration in surface water (Treguer and Jacques, 1992). In Marian Cove, the low $\delta^{15}N$ values during spring to summer clearly indicate the enhanced biologically produced particles resulting from the phytoplankton bloom. The high $\delta^{15}N$ values during the cold period may reflect the mixing particles and/or resuspended particles that consist of zooplankton and higher trophic level species. TOC/TN variation supports this kind of switch of particle sources (Fig. 4f). The low TOC/TN ratios during the spring and summer are likely due to the primary production, resulting from the high flux of micro-sized plankton which experiences short residence time and less oxidation. The high ratios during the fall and winter may be attributed to the dominance of zooplankton, nano-sized plankton, and resuspended sediment particles.

The clear seasonal variation in the deposition of suspended particulates has been reported by sediment trap studies in both shallow and deep Southern Ocean (Fischer et al., 1988; Wefer et al., 1988; Nedwell et al., 1993; Clarke and Leakey, 1996; Cripps and Clarke, 1998; Honjo et al., 2000; Isla et al., 2001; Anadón et al., 2002; Palanques et al., 2002a,b; Walker, 2005). The sharp increase of total mass flux during the warm season, which is typical of the open ocean, was also observed in the shallow marine environment such as Marian Cove, mainly due to the sea-ice coverage during the winter. Even without sea-ice cover, light levels were so low that phytoplankton blooms could not occur. However, more important is the difference in the timing of the maximum deposition of lithogenic particle flux versus biological particle flux during the warm season (Fig. 3b and c). In our study, the biogenic mass flux reaches a maximum before the lithogenic particle flux during the two-year sediment trap deployment. These data indicate that the phytoplankton bloom seems to start with the thawing of sea ice, where the sea-ice edge provides nutrient for production and a stable water column (Abelmann and Gersonde, 1991; Holm-Hansen and Mitchell, 1991; Murphy et al., 1995). Subsequently, as the season progresses, normal phytoplankton blooms sustain the higher biological particle production, while increased influx of meltwater from the coastal region delivers larger quantities of lithogenic particles into the shallow marine environment. Therefore, such differentiated and independent processes between lithogenic particle deposition and biogenic particle deposition occur during the spring to summer months in Marian Cove.

The high productive sea-ice microbial community was represented by the diatom assemblages in the surface sediments in McMurdo Sound, because the supply of terrigenous sediment is limited in this protected basin (Leventer and Dunbar, 1987). In McMurdo Sound, Dunbar et al. (1989) suggested the modern sedimentation pattern, which is dominated by production and settling of biogenic material and reworking by shelf sediments. Recently, the laminated diatom sediments in Mac. Robertson Shelf, Müller Ice Shelf and Palmer Deep have been scrutinized in terms of a seasonal succession, with a vast phytoplankton bloom during the spring followed by lower leads of production and increased lithogenic particle flux during the summer (Gilbert et al., 2003; Maddison et al., 2005; Stickley et al., 2005). Discrete laminae alternating the diatom ooze and terrigenous sediments were interpreted as austral spring and summer signals, respectively. All these works corroborated with our results that the lithogenic particle sedimentation follows the biogenic particle deposition in Marian Cove. Thus, the Marian Cove can be also a good site for identifying the variation of sedimentation pattern associated with regional or global climatic change. Further study on the examination of compositional constituents from the core sediments will be required in this area.

6. Conclusions

Suspended and sinking particulates trapped in Marian Cove, King George Island, show a distinctly seasonal pattern.

Lithogenic particle flux is predominant, comprising more than 95% of the total flux in winter. The lithogenic particle flux is controlled by the amount of snow-meltwater influx from the nearby land, which is directly proportional to the snow accumulation rate during the previous winter. In addition, resuspended particles by tidal currents may contribute to lithogenic flux despite the poor correlation between the lithogenic particle flux and wind speed in the sheltered bay. These lithogenic particles are fine-grained, silt-to-clay sized, consisting of clay minerals that reflect the geology of King George Island. In contrast, biological particle flux is dependent on the intensity of primary production in surface waters. Inter-annual variability of the phytoplankton blooms is a key process that influences the amounts of biogenic material deposited in bottom sediments.

Coastal glaciomarine sedimentation in the shallow water environment of the Antarctic is seasonal, depending largely on the amounts of meltwater, which transports and redistributes sediments. Primary productivity also provides the seasonal biological flux. Based on the two-year sediment trap deployments in Marian Cove, the total mass flux remains relatively low during the winter, whereas these fluxes increase and reach a maximum during the summer. This kind of seasonal variation is typical in the Antarctic environment, as a consequence of the seasonal pattern of sea-ice extent. Most important is the difference in the timing of the maximum biogenic versus lithogenic particle flux during spring and summer. Although coastal glaciomarine sedimentation induced by meltwater is high during the summer, biogenic particle flux precedes lithogenic particle flux, implying that the sea-ice retreat in spring may provide nutrients for ice-edge algal blooms. Continued biological flux can be sustained by the normal phytoplankton blooms during the rest of the summer. Meanwhile, meltwater-induced transport of lithogenic particles increases, reaching the maximum during the summer. However, inter-annual variability controlled by local and regional oceanographic and climatic condition cannot be ruled out.

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