Postglacial marine environmental changes in Maxwell Bay, King George Island, West Antarctica

Boo-Keun Khim & Ho Il Yoon

Sediment textural properties and total organic carbon (TOC) contents of three sediment cores from Maxwell Bay, King George Island, West Antarctica, record changes in Holocene glaciomarine sedimentary environments. The lower sedimentary unit is mostly composed of TOC-poor diamictons, indicating advanced coastal glacier margins and rapid iceberg discharge in proximal glaciomarine settings with limited productivity and meltwater supply. Fine-grained, TOC-rich sediments in the upper lithologic unit suggest more open water and warm conditions, leading to enhanced biological productivity due to increased nutrient-rich meltwater supply into the bay. The relationship between TOC and total sulfur (TS) indicates that the additional sulfur within the sediment has not originated from in situ pyrite formation under the reducing condition, but rather may be attributed to the detrital supply of sand-sized pyrite from the hydrothermal-origin, quartz–pyrite rocks widely distributed in King George Island. The evolution of bottom-water hydrography after deglaciation was recorded in the benthic foraminiferal stable-isotopic composition, corroborated by the TOC and lithologic changes. The $\delta^{18}O$ values indicate that bottom-water in Maxwell Bay was probably mixed gradually with intruding ^{18}O-rich seawater from Bransfield Strait. In addition, the $\delta^{13}C$ values reflect a spatial variability in the carbon isotope distribution in Maxwell Bay, depending on marine productivity as well as terrestrial carbon fluxes by meltwater discharge. The distinct lithologic transition, dated to approximately 8000 yr BP (uncorrected) and characterized by textural and geochemical contrasts, highlights the postglacial environmental change by a major coastal glacier retreat in Maxwell Bay.

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During the last decade, marine geological and geophysical researchers have carried out extensive bathymetric surveys around the continental shelves of the Antarctic Peninsula which contain a portion of the marine-based West Antarctic Ice Sheet (Domack & Ishman 1993; Pudsey et al. 1994; Pudsey & Camerlenghi 1998; Shipp et al. 1999; Canals et al. 2000). The incised glacial troughs observed on the continental shelves of the Antarctic Peninsula preserve thick sediment fills derived from grounded ice shelves which built up during the last glacial period. Sugden & Clapperton (1977) have suggested that during the Last Glacial Maximum many ice caps formed on the South Shetland Islands, which were separated from the Antarctic Peninsula Ice Sheet by the deep Bransfield Strait.

The timing of the onset of deglaciation in the

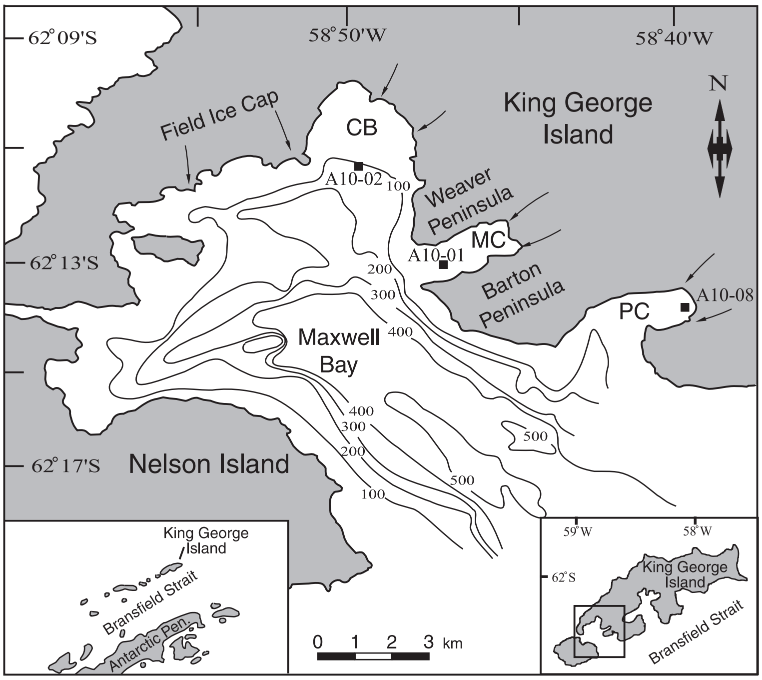

Fig. 1. Core sites and bathymetry of Maxwell Bay, King George Island, South Shetland Islands. Arrows represent the current direction of glacier movement. Abbreviations: CB–Collins Bay, MC–Marian Cove, PC–Potter Cove. The bathymetry is in metres.

region of the Antarctic Peninsula, particularly the South Shetland Islands, is still subject to debate. Based on the sediment accumulation in the several freshwater lakes of the ice-free basin, different opinions on the Holocene glacial and palaeoclimate history of the South Shetland Islands have been offered. Some investigators argue that the present-day warm environment dates back to about 5000 - 6000 yr BP (Mäusbacher et al. 1989; Björck et al. 1991; Björck et al. 1993). Martinez-Macchiavello et al. (1996) corroborated the complete deglaciation on King George Island by ca. 6000 yr BP. In contrast, it has been reported that deglaciation generally commenced in the South Shetland Islands before at least 10 000 yr BP (John 1972; Sugden & Clapperton 1986). Clapperton & Sugden (1982) proposed that the extensive glaciers in the South Shetland Islands were developed at about 9500 yr BP. In addition, Mäusbacher et al. (1989) reported that the last deglaciation occurred between 9000 and 5000 yr BP in King George Island, based on the dates constrained with the lake sediments.

During the glacial period, the ice sheet expanded to the continental shelves, leading to the formation of consecutive prograding shelf edge clinoforms indicatative of subglacial and proglacial sediment gravity flow deposition (Larter & Vanneste 1995). In contrast, during deglaciation, the ice sheet rapidly retreated from the continental shelves, as substantiated by subglacial geomorphic features. Postglacial warming caused the collapse of grounded ice followed by increased meltwater discharge from the neighbouring coastal margins. This meltwater delivered large amounts of fine-grained particles to the continental shelves via shallow marine bays and fjords (Pudsey 2000; Yoon et al. 2000; Taylor et al. 2001). Thus, the shallow marine bays and fjords record such palaeoclimatic changes. However, information on the deglacial palaeoceanographic features of these fjords in King George Island is still limited.

Fjord sediments typically contain the potential records of past biotic, climatic and glacial fluctuations (Syvitski 1989). The shallow areas of the Antarctic Peninsula region, especially in fjords, bays and coves, are the appropriate place to investigate deglacial marine environmental change. Advances and retreats of grounded ice in such environments are key factors determining depositional processes and sediment distribution (Yoon et al. 1997; Kirby et al. 1998; Pudsey 2000). Recently, Li et al. (2000) investigated surface textures of foraminiferal tests in Maxwell Bay, King George Island, located in the South

Shetland Islands (Fig. 1). They have reported that the sea level rise and concomitant influx of open ocean waters during deglaciation led to a strong dissolution of foraminiferal tests. The retreat of coastal glaciers increased meltwater flux into the bay, resulting in higher biological productivity (Domack & Ishman 1993; Domack & McClennen 1996; Shevenell et al. 1996; Kirby et al. 1998). Thus, higher rates of organic matter accumulation may have played an additional role in the carbonate dissolution due to porewater acidification by organic matter oxidation.

In this study, we widen the palaeoenvironmental study of postglacial sediments by using new data concerning grain size and the geochemistry of postglacial sediments, as well as stable-isotope composition of benthic foraminifera, and by establishing the chronology with accelerated mass spectrometry radiocarbon dates obtained from three sediment cores in Maxwell Bay (Fig. 1). These results contribute to the reconstruction of the deglacial and Holocene environments of the coastal area of King George Island.

The study area

King George Island's Maxwell Bay is 14 km long and 6 - 14 km wide (Fig. 1). It is one of the deep, U-shaped fjords found along the southern margin of the South Shetland Islands. It is surrounded by ice cliffs creeping from the low profile ice cap of Fildes Peninsula and Nelson Island. Maxwell Bay is separated from Bransfield Strait by a deep (>430 m water depth) submarine sill. Water depth increases gradually from the coastline to the 200 m isobath, and then steeply to the 550 m isobath.

At 65° S, the study area experiences a slightly more moderate climate (cold temperate to subpolar) compared to the main Antarctic Peninsula region. The surface waters of Maxwell Bay freeze regularly in winter, from late July to mid-September. A surface layer of warmer (1.04 to 0 °C), less saline (33.85 to 34.0 psu) and lower $\delta^{18}O$ (−0.44 to −0.30 ‰) water overlies a colder (0 to −0.34 °C), more saline (34.0 to 34.53 psu) and higher $\delta^{18}O$ (−0.30 to −0.17 ‰) subsurface water mass (Khim et al. 1997). The temperature and salinity differences between the surface and subsurface waters are approximately 1 °C and 0.6 psu, respectively. The $\delta^{18}O$ values are below –0.30 ‰ in the surface water and above –0.20 ‰ in the subsurface water. Because Maxwell Bay is connected directly to Bransfield Strait over a relatively deep submarine sill, Bransfield Strait water (open ocean water) is well circulated with the subsurface water in the bay (Hong et al. 1991; Khim et al. 1997). The surface water is governed by the freshwater input from glacial melting and surface runoff.

Several tributaries were developed in Maxwell Bay, including Marian Cove and Potter Cove in the north-east and Collins Bay in the north (Fig. 1). From late October, sea ice begins rapidly to break up and numerous icebergs are scattered in Maxwell Bay. Active iceberg calving from the tidewater glacier terminus was observed in Collins Bay during the austral summer (Yoon et al. 1998). Small valley glaciers draining into Marian Cove also deliver icebergs and large volumes of turbid meltwater during the summer months (Yoon et al. 1998). Potter Cove, a tributary inlet near the entrance of Maxwell Bay, is characterized by large meltwater discharge, but no calving of icebergs has been observed (Klöser et al. 1994). Most ice-rafted debris therefore originates from the calving of icebergs off the edges of glaciers, whereas fine-grained particles are discharged by meltwater during the summer season. The bay becomes completely ice-free during the summer (November–February), leading to increased primary biological production.

Materials and methods

In 1997, three gravity cores were collected from Collins Bay (A10-02), Marian Cove (A10-01) and Potter Cove (A10-08) in Maxwell Bay aboard the RV *Yuzhmorgeologiya* during the Tenth Korea Antarctic Research Expedition (Fig. 1, Table 1).

Each core was cut in the laboratory and then subsampled at 5-cm intervals for analyses of grain size, total organic carbon (TOC) and total sulfur (TS). Grains larger than 63 µm (gravel and sand) were separated by wet sieving and classi-

Table 1. Location, water depth, and core length of sediment gravity cores that were obtained in the Maxwell Bay.

Core	Latitude	Longitude	Water depth	Core length
A10-01	62° 13.0' W	58° 47.5' S	85 m	235 cm
A10-02	62° 11.3' W	58° 49.7' S	105 m	270 cm
A10-08	62° 13.7' W	62° 39.7' S	45 m	105 cm

fied by dry sieving. Grains smaller than 63 µm (silt and clay) were analysed using a Micromeritics Sedigraph 5100D. After removing $CaCO_3$ by 10% HCl from the bulk sediment powders, TOC and TS were measured using a Carlo-Erba NA-1500 Elemental Analyzer at KORDI.

Oxygen and carbon stable isotopic values were determined on the tests of benthic foraminifera (*Globocassidulina biora*), ranging in size from 150 to 250 µm. Because some foraminiferal tests show the dissolution texture (Li et al. 2000), specimens for analyses were carefully selected. After treatment at 350 °C for 1 hour under vacuum to remove organic matter, samples were then reacted with H_3PO_4 at 90 °C in an on-line automated carbonate CO_2 preparation device connected to a VG PRISM II mass spectrometer at the University of California, Santa Barbara. The instrumental precisions of isotopic measurement are ±0.11‰ for $\delta^{18}O$ and ±0.09‰ for $\delta^{13}C$ based on the internal standards. All values are expressed in the δ notation in accordance with the V-PDB standard (Craig 1957; Coplen 1996).

Accelerator mass spectrometry (AMS) radiocarbon (^{14}C) ages were measured at the Institute of Geological and Nuclear Sciences, New Zealand, using the acid-insoluble organic matter fraction of bulk sediments.

Results

Chronology of core sediments

Because we did not collect box cores for precise age determination of surficial sediments, the core-top ages of each gravity core are estimated by the extrapolation of the regressions based on the measured ^{14}C ages (Table 2). The extrapolated ages of core-tops are approximately 5061 yr BP for core A10-01, 3555 yr BP for core A10-02 and 5128 yr BP for core A10-08 (Fig. 2). These extrapolated surface ages are significantly larger than the typical reservoir correction for Antarctic marine environments, although the ocean reservoir correction may have changed during the glacial–interglacial cycles. In general, the ocean reservoir effect for the Antarctic marine carbonates accounts for about 1200 to 1300 years (Gordon & Harkness 1992; Berkman & Forman 1996). However, it has been reported that radiocarbon ages obtained from acid-insoluble organic fraction of surficial sediments are substantially older and often range between 2000 and 5000 years (Domack 1992; Andrews et al. 1999; Pudsey & Evans 2001). Such large discrepancies between the apparent reservoir correction and the measured ^{14}C ages from sediment organics may be attributed to the old carbon contamination caused either by the liberation of CO_2 stored in the ice sheets (Domack et al. 1989), along with the uptake of "old" dissolved inorganic carbon by diatoms (Gibson et al. 1999), or by the assimilation of dissolved inorganic carbon by diatoms during CO_2 limiting conditions (Tortell et al. 1997). Otherwise, the core-top sediments seem to be lost during the coring process. Therefore, in this study, we give the uncorrected measured radiocarbon ages in describing the downcore var-

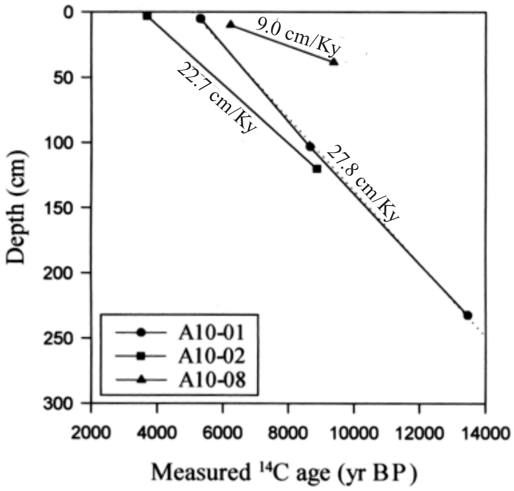

Fig. 2. Relationship between measured AMS ^{14}C ages (bulk sediments) and core depths (see Table 2). Estimated linear sedimentation rates are shown for each core. The dotted line represents the sedimentation rate of core A10-01 averaged from two segments.

Table 2. AMS ^{14}C radiocarbon ages measured on bulk sediment organic carbon.

Core	Depth (cm)	Measured ^{14}C age (yr BP)	$\delta^{13}C$ (‰)	Lab code
A10-01	5	5313±71	–31.6	NZA8021
	103	8649±70	–35.8	NZA8030
	232	13461±98	–40.0	NZA8045
A10-02	4	3688±73	–27.7	NZA8025
	120	8851±73	–34.1	NZA8026
A10-08	10	6234±69	–32.3	NZA8022
	38	9365±93	–38.6	NZA8023

iation in sedimentological and geochemical properties.

Sedimentation rates of core sediments

Linear sedimentation rates were calculated by interpolation between the ^{14}C-dated levels, although sedimentation rates might vary during deposition (Fig. 2). The apparent linear sedimentation rates are 27.8 cm/Ky (thousand years) for core A10-01, 22.7 cm/Ky for core A10-02 and 9.0 cm/Ky for core A10-08. The sedimentation rates in cores A10-01 and A10-02 are comparable to those of glacimarine sediments in Marguerite Bay and Gerlache Strait in the Antarctic Peninsula (20 - 50 cm/Ky; Harden et al. 1992), but still one order of magnitude lower than those in Lallemand Fjord, Andvord Bay and Granite Harbor (100 - 250 cm/Ky; Leventer et al. 1993; Domack & McClennen 1996; Kirby et al. 1998; Taylor et al. 2001). The sedimentation rate in Porter Cove (core A10-08) is one order of magnitude lower than in other areas of Maxwell Bay, in spite of the meltwater discharge from many small creeks (Klöser et al. 1994). Such a low sedimentation rate may be due to low amounts of suspended particles delivered by meltwater from the discharge basin. Alternatively, the suspended particles delivered into Potter Cove may transit to Maxwell Bay because of a small depositional accommodation and the tidal action.

Grain size of core sediments

Downcore variation of sediment properties, including granulometric components and geochemical properties such as TOC and TS, are shown in Fig. 3. Measured AMS radiocarbon ages are also added on the core profiles; there is no reversal in the age throughout the cores. Based on sediment properties, all three cores can be divided clearly into two lithologic units: (1) an upper unit composed of fine-grained mud with scattered, minor ice-rafted debris; and (2) a lower unit composed mostly of diamicton. X-radiographs of core sediments clearly identify the distinct textural contrast of the two lithologic units (Fig. 4).

The upper unit is dominated by silt and clay in cores A10-01 and A10-02, but sand and gravel occur in core A10-08—as much as 25 % in content (Fig. 3). The coarse fraction in core A10-08 is probably accounted for by the core's location close to the coast, where terrigenous clastic particles are common. The lower unit of diamicton is characterized by mixed sediments with large amounts of gravel and sand (Fig. 3). The near absence of gravel in core A10-02 may be attributed to the limited activity of the coastal glaciers. Although the vertical profile of mean grain size shows an overall decreasing trend, more frequent fluctuations occur in the lower unit due to the diamictic sediment composition. The distinct textural contrast between the upper and lower lithologic units is also identified by the mode of change in individual grain size classes (Fig. 5). Such a change in grain size mode reflects variation with respect to the sediment transport mechanisms. The formation of the lower unit can be explained by advanced glacier margins with rapid iceberg discharge and limited meltwater supply. Because it is generally difficult to distinguish subglacial tills from glacial marine diamictons based solely on visual appearance or a single attribute of the sediments (see Licht et al. 1999), further analytical research on diamictons is necessary to constrain the interpretation of depositional environments.

TOC, TS and their relationship with grain size data

Downcore variation of TOC content shows upwardly increasing values, matching the lithologic changes (Fig. 3). In the diamicton, TOC contents are less than 0.1 %, whereas the fine-grained sediments contain as much as 0.5 %. Such a high TOC value is similar to that of the reported modern surface sediments from Andvord Bay (Domack & Ishman 1993). TOC contents usually depend on sediment grain size. Most of the organic matter in shallow marine sediments is closely linked to the mineral matrix, occurring as organic coating adsorbed on the mineral surfaces (Keil et al. 1994). Thus, a negative correlation between TOC and sediment coarseness is almost universally observed in the noncarbonate sediments in marine and lacustrine environments. Figure 6 shows the relationship between TOC contents and mean grain size. TOC contents of the core sediments are largely determined by the amounts of clay particles in the sediments, although overall TOC content is mostly low. The positive linearity between the two parameters is expected in spite of the different correlation coefficient in the size fractions.

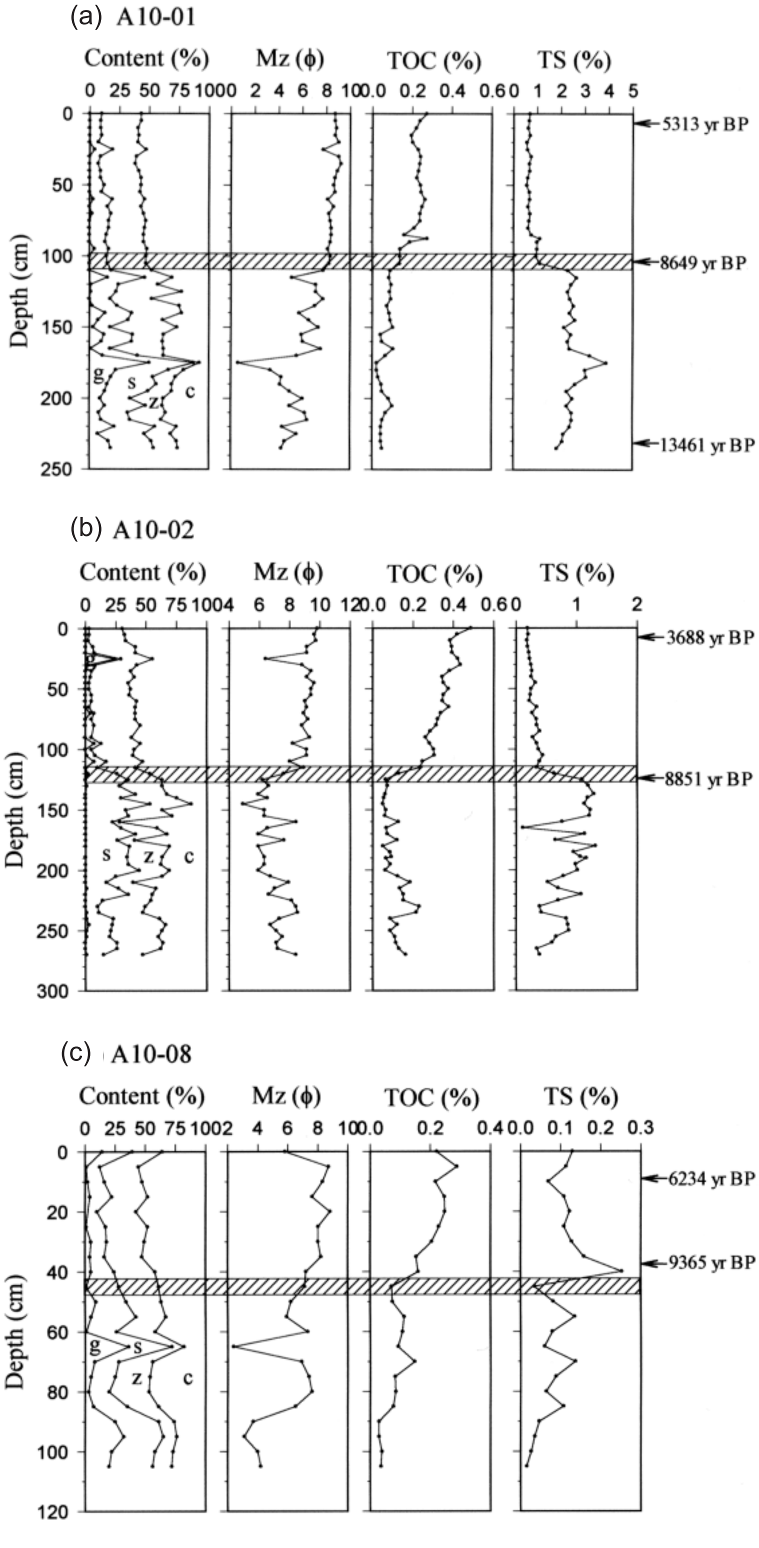

Fig. 3. Vertical profiles of sediment properties (granulometric content, mean grain size, total organic carbon and total sulfur contents) from cores (a) A10-01, (b) A10-02 and (c) A10-08. Measured radiocarbon ages are indicated at the right side of column. The hatched area represents the transition zone from diamicton to mud.

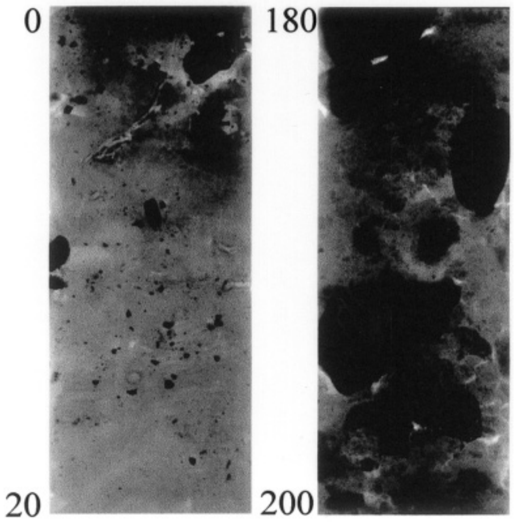

Fig. 4. X-radiograph of core A10-01 showing the lithologic feature of upper (fine-grained mud with scattered ice-rafted debris) and lower sedimentary (mostly diamictons) units.

It has been suggested that the ratio of organic carbon to pyrite sulfur (TOC/TS) can be used to distinguish between marine and freshwater sediments (Berner & Raiswell 1984). In normal marine sediments, the sulfur mainly originates from organic matter and/or pyrite minerals. The limiting factor for pyrite formation under normal oxic seawater conditions is the amount of organic matter, which determines reducing conditions in the near-surface sediments (Berner 1982). Figure 6 also shows the interesting relationships between TOC and TS in core sediments. Two divided opposite trends between TOC and TS are observed in core A10-08 (Fig. 6f), which is difficult to explain. In contrast, the other two relationships of cores A10-01 and A10-02 are more hyperbolic (Fig. 6d, e). In the case of the hyperbolic relationship, the pyrite seems to be the main contributor of surplus sulfur because of the low TOC content and therefore the insufficient formation of sulfide minerals in situ in the reducing environment. In core sediments of A10-01 and A10-02, high TS contents are closely related to the sand fraction (Figs. 4, 6), implying that terrestrial material seems to be a main source for sulfur. The increase of TS content can be attributed to an input of terrestrial pyrite of hydrothermal origin—quartz–pyrite rocks, which have been recognized and described by many inves-

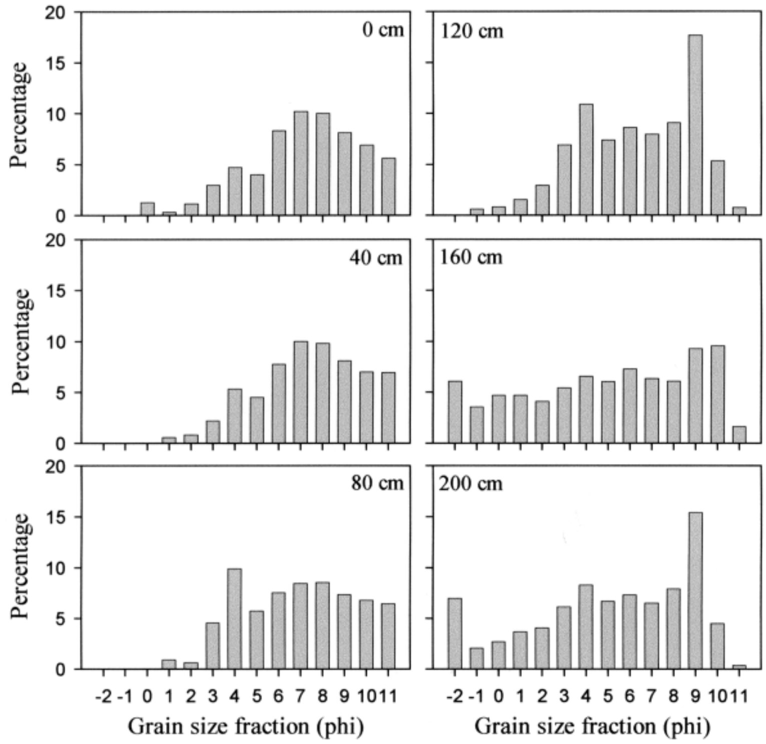

Fig. 5. Variation of grain size class distribution in sediment core A10-01. Histogram of grain size classes represents the change of mode from lower to upper lithologic units.

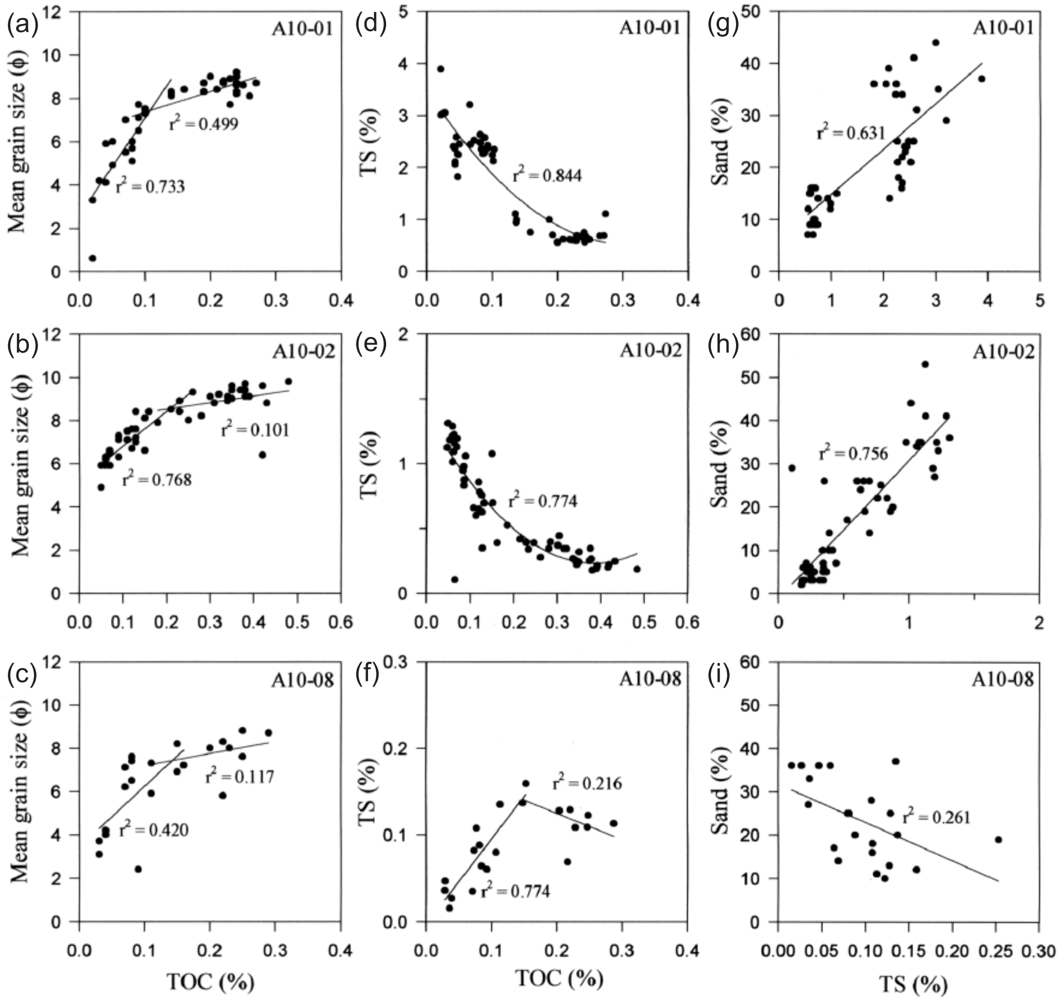

Fig. 6. (a - c) Relationships between total organic carbon (TOC) and mean grain size, (d - f) between TOC and total sulfur (TS), and (g - i) between TS and sand content. The surplus sulfur with low TOC is observed in cores A10-01 and A10-02. High TS contents are closely related to the sand fraction in A10-01 and A10-02, implying that terrestrial material is the main source for sulfur.

tigators on King George Island (Littlefair 1978; So et al. 1995).

Stable-isotope composition of benthic foraminifera

The downcore variation in $\delta^{18}O$ and $\delta^{13}C$ values of benthic foraminifera shows the deglacial transition, similar to the lithologic variation (Fig. 7). The hatched areas mark the transition zone between the lower and upper sedimentary units (Fig. 3). Both $\delta^{18}O$ and $\delta^{13}C$ values vary in a small range (Fig. 8), indicating relatively stable environmental conditions for the stable-isotope compositions. The $\delta^{18}O$ values lie in the small range, between 3.7‰ and 4.1‰. However, some upcore increase in $\delta^{18}O$ values can be identified in the upper unit (Fig. 7), although the increasing trend in $\delta^{18}O$ values is not distinct in core A10-08. The differences of $\delta^{18}O$ values between the upper and lower units are about 0.1‰ for cores A10-01 and A10-02.

The $\delta^{13}C$ foraminiferal values in cores A10-01 and A10-02 vary slightly between 0 and 1‰ (Fig. 8). Clustering of core A10-08 is clearly distinguishable. The $\delta^{13}C$ values show a larger vari-

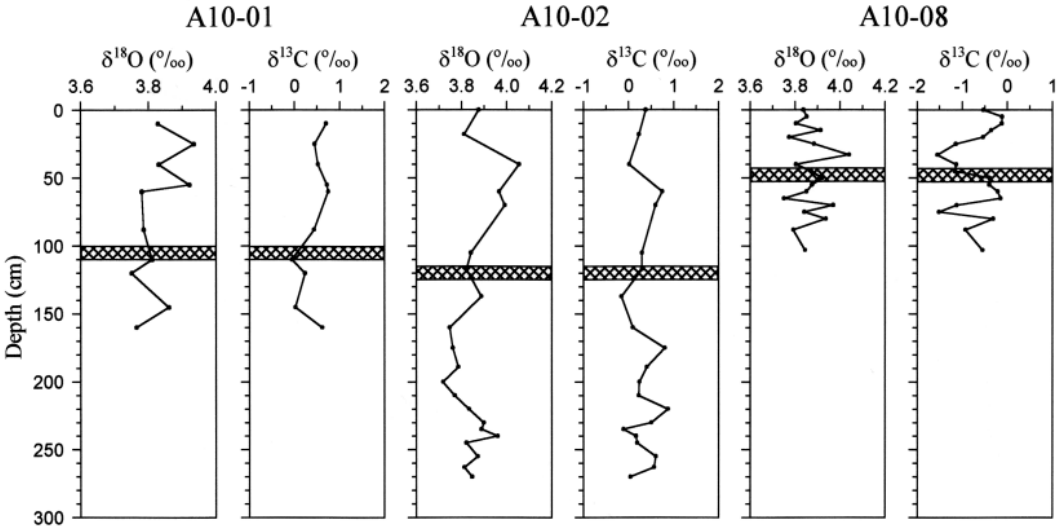

Fig. 7. Downcore variation of stable isotopes in benthic foraminifera. The hatched area represents the transition zone from diamicton to mud.

ation and lighter values of –1.5 to 0 ‰ in this core. This may be due to a depth difference between the core sites, with the shallowest depth of A10-08 influenced by meltwater discharge. All three cores show a gradual increase in $\delta^{13}C$ values in the upper unit, possibly reflecting the inflow of shelf water with sea level rise and glacier retreat (Yoon et al. 2000; Khim et al. 2001). In addition, the higher productivity during the warm post-glacial period enhanced the content of heavy carbon in the seawater carbonate pool (Arthur et al. 1983). Fluctuations of $\delta^{13}C$ values throughout the lower unit of cores A10-02 and A10-08 are likely due to redeposition of pre-glacial sediments, through reworking of the coarser particles. Otherwise, the poor preservation of foraminiferal specimens and their secondary alteration may affect the isotope signals.

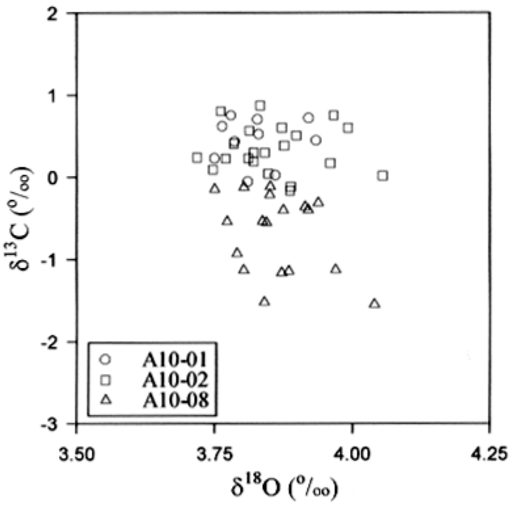

Fig. 8. Biplot of $\delta^{18}O$ and $\delta^{13}C$ values of benthic foraminifera.

Discussion

Postglacial marine environmental change in Maxwell Bay

Sedimentary and geochemical properties show that all three cores in Maxwell Bay are characterized by two lithologic units (Fig. 3). The upper unit consists of fine-grained mud with scattered, minor ice-rafted debris. The lower unit is mostly diamicton. The main boundaries of the lithologic changes from diamictons to the fine-grained mud are at downcore depths of approximately 105, 120 and 45 cm in cores A10-01, A10-02 and A10-08, respectively. Among three cores, the transitional boundaries of A10-01 and A10-02 are comparable in age: 8649 and 8951 yr BP, respectively. Based on previous studies in the Antarctic Peninsula, the fine-grained sediments comprising the upper unit document open water conditions of an ice-distal environment, whereas the

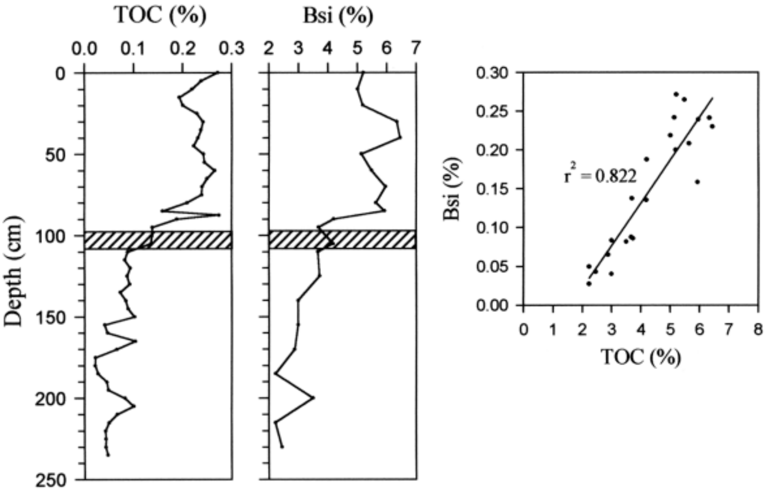

Fig. 9. Comparison of vertical variation between total organic carbon (TOC) and biogenic silica (Bsi) (modified from Kim et al. 1999; printed with permission of *Geosciences Journal*). The strong positive relationship indicates a high biological productivity in the upper unit, largely composed of diatoms.

coarse diamictons in the lower unit record an ice-proximal environment (see Shevenell et al. 1996; Yoon et al. 1997; Kirby et al. 1998; Pudsey 2000; Taylor et al. 2001). Thus, the accumulation of fine-grained mud in the upper unit was likely influenced by sediment-deriven meltwater influx during a warm climate regime after the completion of deglaciation (Kirby et al. 1998). This indicates fast deglaciation, probably due to a sea level determined ice break-up and subsequent calving (Yoon et al. 2000). The resulting upper unit in the sediment cores is characterized by relatively high TOC, derived from enhanced productivity concomitant with nutrient enrichment (Fig. 3).

In polar fjord sediments, organic carbon enrichment may result from the increased vertical settling of organic carbon due to high productivity in surface water (Domack & McClennen 1996; Kirby et al. 1998). Otherwise, less dilution by more terrigenous input associated with ice-proximal meltwater plumes and/or reworking of bottom sediments may enhance the preservation of TOC within the sediments (Shevenell et al. 1996). The low TOC contents in the lower unit may be attributed to the limit and reduction of organic carbon production mainly due to the advanced coastal glacier margin, with extensive sea ice coverage inhibiting primary production in surface water. This period corresponds roughly with a cold condition recorded on nearby Livingstone Island and in lake sediments on James Ross Island (Björck et al. 1996). It also matches a cold event documented in the sediment cores from Lallimand Fjord, Antarctic Peninsula (Shevenell et al. 1996). In contrast, the high TOC contents in the upper unit may be caused by the enhanced primary production in the surface water, due to a higher delivery of nutrients by meltwater discharge during the warm period (Yoon et al. 2000; Khim et al. 2001; Taylor et al. 2001). The increased productivity in the upper unit is also supported by the biogenic silica (Bsi) content and positive relationship between the Bsi and the TOC (Fig. 9). Such high TOC is largely accounted for by increased diatom abundance. Thus, the clear disparity in TOC contents corresponding to lithologic changes reflects a range of depositional environments, from ice-proximal to ice-distal condition (Fig. 3).

The environmental transition from diamicton to fine-grained sediments is also supported by $\delta^{18}O$ variation in benthic foraminifera from shallow marine environments, although it is tenuous because of complex hydrographic parameters determining the stable-isotope compositions (Arthur et al. 1983). In particular, dominant incorporation of oxygen from freshwater to the carbonate precipitation complicates the determination of the temperature effect and the $\delta^{18}O$ content of seawater. Furthermore, stable temperatures in Antarctic Ocean waters could hardly add any noticeable temperature-controlled variation in the carbonate stable-isotope composition (Charles & Fairbanks 1990). Today, the bottom-water temperature in Maxwell Bay is stable and consistently lower than 0 °C (Khim et al. 1997). During the deglacial period, the bottom-water temperature may have been higher. Here, we assume that benthic foraminifera in this environment mostly represent bottom-water stable-isotope properties by inheriting the $\delta^{18}O$ and $\delta^{13}C$ compositions of ambient seawater at the time of precipitation. During the postglacial time, the increasing $\delta^{18}O$ values may be due to the marine seawater intruding into Maxwell Bay from Bransfield Strait, not the decrease of bottom-water temperature. Although the surficial meltwater discharge increases with warming, the bottom-water in Maxwell Bay is still connected with the saline water of Bransfield Strait. Higher $\delta^{18}O$ values (−0.2 ‰) of shelf water in the strait are contrasted with those (−0.3 ‰) of seawater in Maxwell Bay (Khim et al. 1997). We infer that with the retreat of grounded coastal glaciers and the reduction of sea ice coverage, more seawater from Bransfield Strait entered Maxwell Bay, resulting in heavier $\delta^{18}O$ values in benthic foraminifers. However, later in the Holocene, $\delta^{18}O$ values decreased, probably due either to higher temperatures or to stronger dilution by meltwater.

Holocene marine environmental change in South Shetlands Islands

Marine geological and geophysical studies have shown that the shallow marine environments around the Antarctic Peninsula were covered by grounded ice sheets during the last glaciation (Domack & Ishman 1993; Pudsey et al. 1994; Pudsey & Camerlenghi 1998; Shipp et al. 1999). In particular, sedimentary and lithologic investigations have demonstrated that Lapeyrere Bay (Anvers Island), Cierva Cove (Danco Coast), Lallemand Fjord, Andvord Bay and Brialmont Cove preserve a characteristic change in sediment lithology type from glacier-proximal coarse-grained sediments to distal sandy, biosiliceous muds (Domack & McClennen 1996; Kirby et al. 1998; Khim et al. 2001; Taylor et al. 2001). Downcore variation in TOC complements the interpretation of depositional environments and allows the reconstruction of palaeoenvironmental conditions. The elevation of TOC contents represents a time when the vertical flux of organic carbon throughout the fjord was higher, under favourable preservation conditions.

The lithologic transition from coarse-grained diamicton to homogeneous mud in Maxwell Bay reflects a major coastal-ice retreat, dated to approximately 8000 yr BP. A similar date was obtained from the lake sediment cores in King George Island (Mäusbacher et al. 1989). Assuming that the ice sheet break-up was bathymetrically controlled by ice retreat toward the island, we infer a similar time for the glacimarine–marine transition in King George Island; this is also supported by dates from the marine cores in Admiralty Bay, King George Island (Khim et al. 2001). During postglacial period, the ground-line retreating of the coastal glacier and the diminished sea ice coverage resulted in rapid and enhanced primary production in Maxwell Bay. With the increased productivity, abundant benthic foraminifera were deposited in the postglacial sediment, with an upcore trend of increasing TOC (Fig. 3; Li et al. 2000). Judging from the steady increase in TOC, the climate became gradually warmer. Regionally, this interpretation is corroborated by lake sediments from King George Island (Schmidt et al. 1990) and James Ross Island (Björck et al. 1996). It also corresponds to the period of open marine conditions recorded in the sediment core from Lallimand Fjord, Antarctic Peninsula (Shevenell et al. 1996).

The postglacial records of South Shetland Islands, including Maxwell Bay of King George Island, are comparable to those of the fjords of the Antarctic Peninsula, and East and West Antarctica, revealing both similarities and anomalies between the regions (Domack & McClennen 1996). The sedimentological and geochemical data generally represent a transition from ice-proximal to open marine deposition. This is strongly supported by the presence of the ice-associated diatom assemblage in open marine environments (Leventer et al. 1993; Taylor et al. 2001). In addition, the increasing TOC suggest increasing primary production and may reflect dilution of this signal due to increased siliclastic sedimentation. During the mid-Holocene, the climate generally became warmer and more humid, showing high productivity peaks in the marine records. In particular, lake sediment data from South Georgia (Rosqvist et al. 1999) and James Ross Island (Björck et al. 1996), and even marine sediments in the Ross Sea, suggest that atmospheric temperatures were warmer than present during that time.

Conclusions

Sediment textures and geochemical properties of three sediment cores from Maxwell Bay, King

George Island, record changes in glacimarine environments, which occurred during coastal glacier retreat, accompanied by increased meltwater discharge and postglacial warming. Coupled lithologic and geochemical changes demonstrate that the lower diamictons represent advanced glacier margins and/or extensive sea ice cover, which limited primary biological production and meltwater supply. In contrast, the younger unit, composed mainly of fine-grained particles, indicates more open water and warmer conditions, favourable for enhanced production. Comparison between TOC and TS suggests that the additional sulfur, characteristic of the lower unit, originated from the nearby hydrothermal-origin, quartz–pyrite rocks of King George Island, but not from the in situ pyrite formation under reducing conditions. Benthic foraminiferal stable-isotope composition indicates that bottom-water conditions in Maxwell Bay were affected by shelf water inputs from Bransfield Strait after deglaciation. The lithologic transition occurring at about 8000 yr BP (^{14}C age), in the mid-Holocene, supports previous results reported for King George Island.

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