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# 남극반도 주변지역의 고기후변화에 따른 빙하퇴적환경 연구

# Glaciomarine Sedimentary Environment and Recent Glacial History of Maxwell Bay and Marian Cove, King George Island, Antarctica

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# 제 출 문

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본 보고서를 '남극반도 주변지역의 고 기후변화에 따른 빙하퇴적환경 연구' 과제의 최종보고서로 제출합니다.

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# Depositional environment of near-surface sediments, King George Basin, Bransfield Strait, Antarctica

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**Abstract** Four sediment cores were collected to determine the depositional environments of the King George Basin northeast of Bransfield Strait, Antarctica. The cored section revealed three distinct lithofacies: laminated siliceous ooze derived from an increased paleoproductivity near the receding sea-ice edges, massive muds that resulted from hemipelagic sedimentation in open water, and graded sediments that originated from nearby local seamounts by turbidity currents. Clay mineral data of the cores indicate a decreasing importance of volcanic activity through time. Active volcanism and hydrothermal activity appear to be responsible for the enrichment of smectite near the Penguin and Bridgeman Islands.

## Introduction

The King George Basin is a deep (up to 2000 m), small, morphotectonic depression northeast of the Bransfield Strait (Fig. 1). It is bounded to the northwest by a steep slope of the South Shetland Islands platform and by seamount walls to the northeast (Fig. 1). Active submarine and subaerial volcanism, associated with back-arc spreading in the basin, have generated the Penguin and Bridgeman islands as well as numerous seamounts and contributed volcanic ash to the basin floor in the form of gravity-flow and/or airfall deposits (Anderson and Molnia 1989; Singer 1987). The contribution of clastic sediments discharged from the adjoining landmasses is relatively insignificant except during periods of episodic meltwater streams.

During the austral summer, the basin receives large amounts of biogenic materials seasonally produced by high planktonic activity in the surface water, with an average production rate of 1.6 g/cm$^2$ day (Gersonde and Wefer 1987; Wefer et al. 1988). On a regional scale, sea ice generally undergoes seasonal growth and decay, controlling surface water productivity; during the winter (July–October) the Bransfield Strait remains ice-covered with limited productivity, whereas during the summer (December–April) the area is completely ice-free, giving rise to increased productivity. We would expect that these processes would be recorded by the sedimentary structures, textures, mineral composition, and chemical properties of the sediments in the basin.

The major objective of this study is to describe the sedimentary facies of subsurface sediments collected from the King George Basin and to infer the influences of varying environmental factors in the formation of the sedimentary facies, such as the productivity of surface water, sea-ice fluctuations, sediment gravity flows, and limited terrigenous supply.

## Methods

Four 3-m-long piston cores (7 cm in diameter) were collected along a transect across the continental slope off the northern Antarctic Peninsula into the King George Basin, Bransfield Strait, Antarctica (Fig. 1). Cores were split into half for X-radiography and subsampling. Subsamples were analyzed for grain size, total organic carbon, and biogenic silica contents. Clay minerals (< 2 μm) were identified by X-ray diffraction, and the methods of Biscaye (1965) and Carroll (1970) were followed for semiquantitative analyses of clay minerals. Subsampling intervals were selected so as to represent all lithologies apparent in the split cores. X-radiograph analyses as well as visual observations of the split cores were made to identify biogenic and physical sedimentary structures. Total and carbonate carbon were determined using a Carlo Erba NA-1500 Elemental

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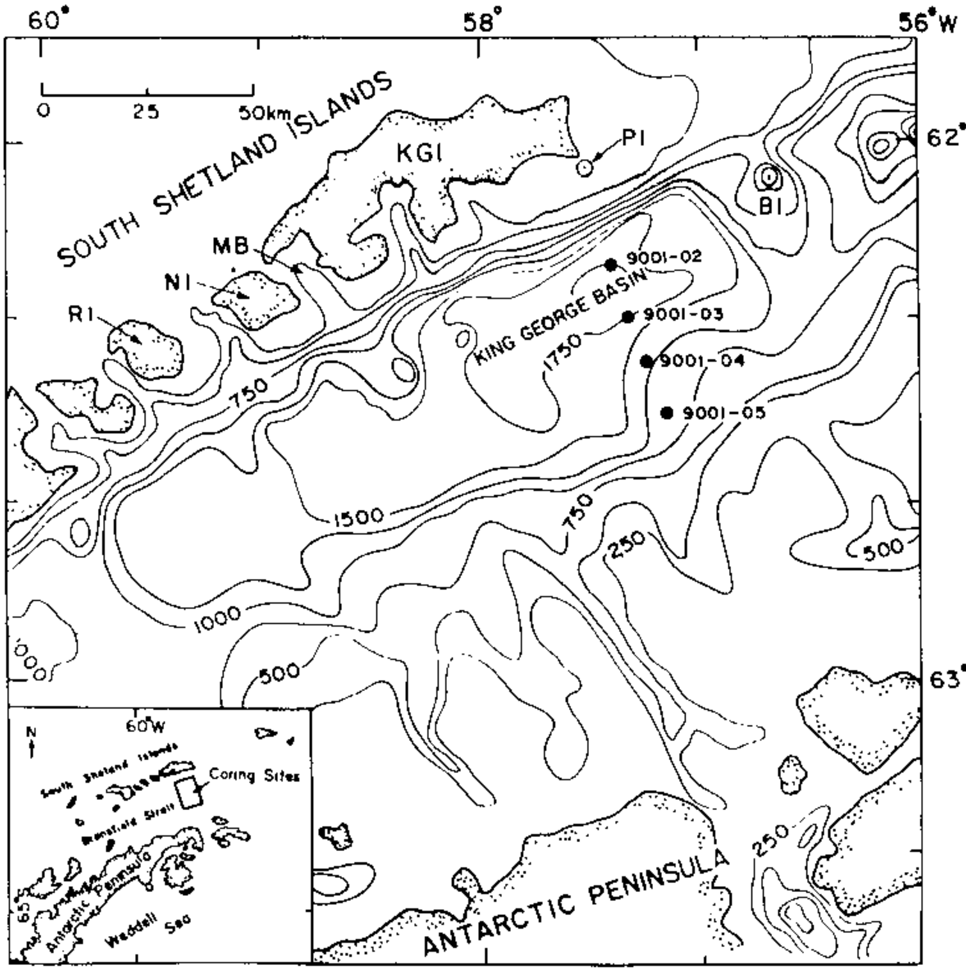


Fig. 1 Bathymetry and core locations in King George Basin, Bransfield Strait. Contours in meters (from Jeffers and Anderson 1990). RI: Robert Island, NI: Nelson Island, MB: Maxwell Bay, KGI: King George Island, PI: Penguin Island, BI: Bridgeman Island

Analyser to measure the $CO_2$ formed by combustion at 1100 C, and treated by hot 10% HCl, respectively (Heath et al. 1977). Organic carbon was obtained by measuring and calculating the difference between the total carbon and the carbonate carbon. Biogenic silica was determined by the sequential leaching method of DeMaster (1981). Sulfide sulfurs were measured by precipitating sulfur as barium sulfate (Vogel 1975).

## Results

### Sedimentary facies

The sediments of the studied core sections reveal lithologies that consist of siliceous ooze, massive muds, and graded sediment interbedded with massive muds (Fig. 2).

Siliceous ooze occurs consistently near the base of all cores and is generally gray to brownish gray and well

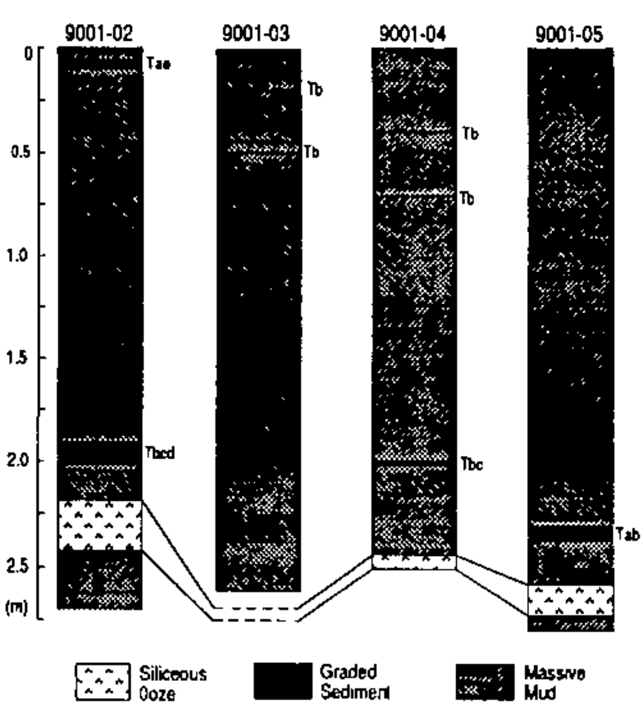


Fig. 2 Lithological logs of sediment cores from King George Basin. Note that siliceous ooze layers consistently occur near the base of all cores, whereas graded units, denoted by T, occur randomly through the cores

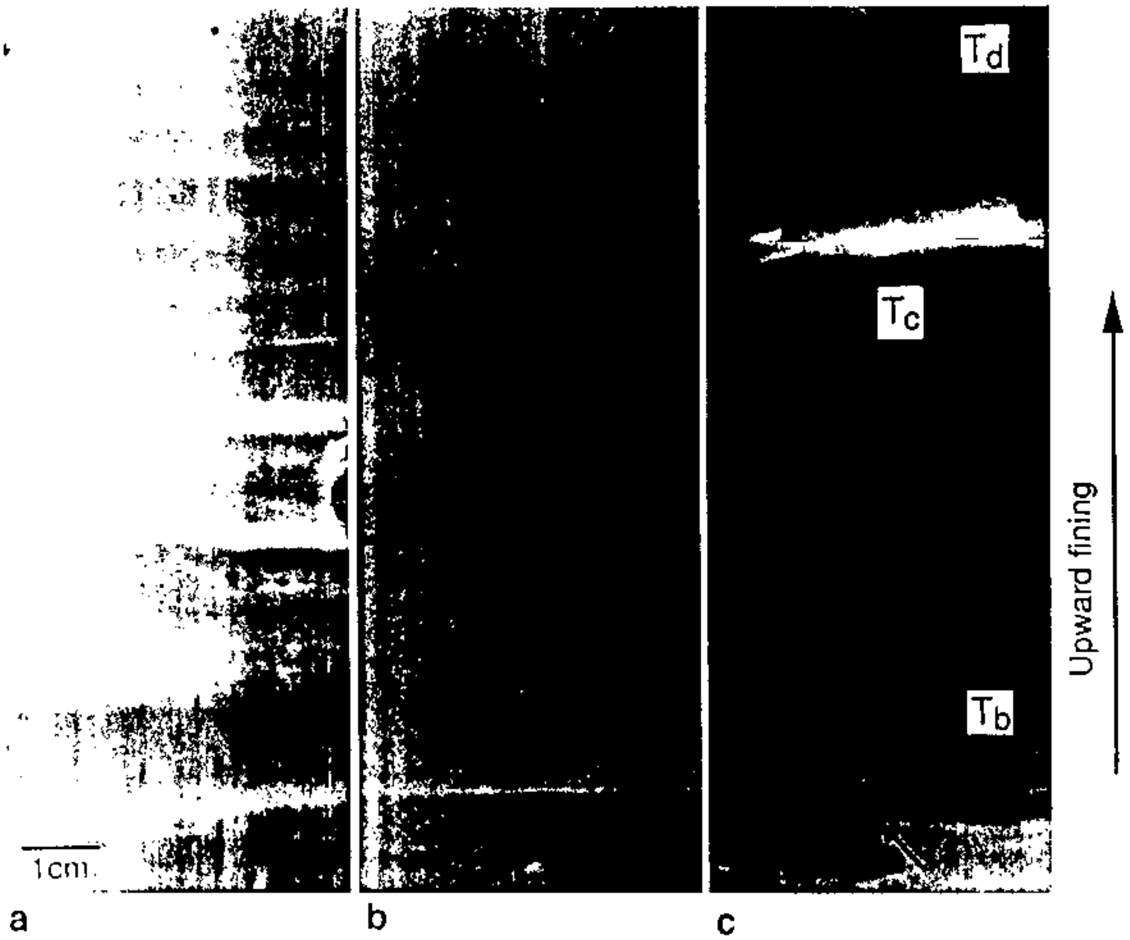


Fig. 3 X-radiographs of cores representing sedimentary facies **a** well-laminated siliceous ooze (light band) alternating with clayey silt (dark band) (core 9001-02, core depth, 246–258 cm); **b** bioturbated massive mud with scattered dropstone as denoted by arrow (core 9001-05, core depth, 118–130 cm), **c** graded sediment (core 9001-02; core depth, 171–183 cm) consisting of parallel-laminated coarse sand ($T_b$) and microripple cross-laminated medium to coarse sand ($T_c$) being overlain by the repetitive sequence of parallel-laminated clayey silt ($T_d$). The arrow near the bottom indicates an erosional surface

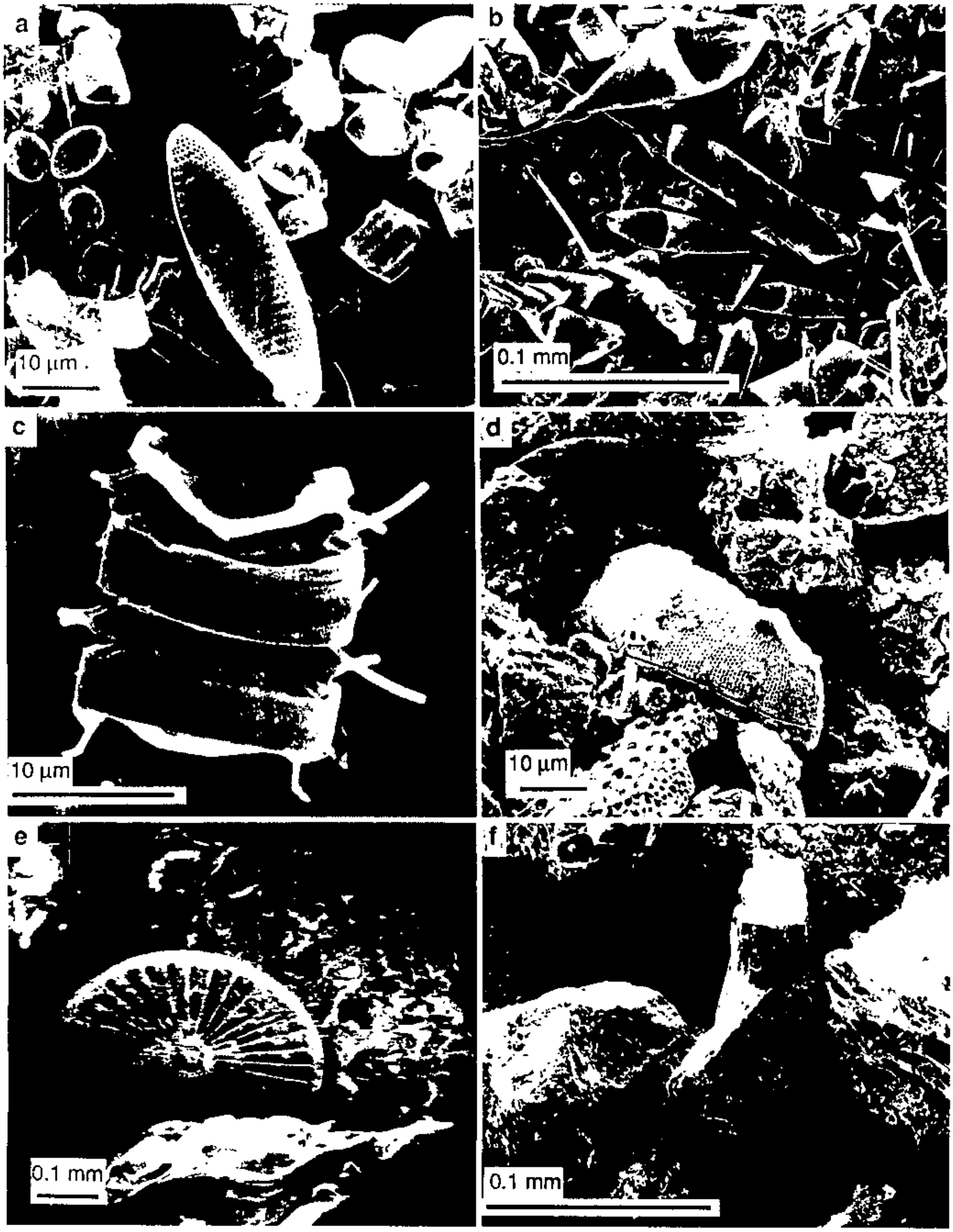
laminated. Most laminae are between 0.5 and 5.0 mm thick and consist of alternating couplets of diatom ooze and clayey silt (Fig. 3a). Siliceous ooze is primarily composed of well-preserved *Nitzschia* sp., *Rhizosolenia* sp. and *Chaetoceros* sp. in a chain form (Fig. 4a–c). Some laminae even exclusively contain a nearly monospecific assemblage of *Rhizosolenia* sp. and/or *Chaetoceros* resting spores. Clayey silt laminae consist mainly of terrigenous particles such as quartz and volcanic glass.

Massive muds comprise the larger portion of the core sections and show a slight increase in the amount of terrigenous materials compared to the siliceous ooze (Fig. 2). These sediments consist of olive to dark gray clayey silt to silty clay with a minor amount of biogenic opal. Most of the biogenic opal is composed of fragmented diatom frustules and debris (Fig. 4d); silicoflagellates, radiolaria, and sponge spicules are rare (less than 1%). The muds are usually homogeneous, moderately bioturbated, and partly mottled (Fig. 3b). Such sediments occasionally include dark bands or patches that are largely composed of well-preserved diatoms, as seen in the sediments of the siliceous ooze.

Graded sediments occur randomly through the cores and show no definite core-to-core correlations (Fig. 2). They are largely composed of laminated fine sand-to-gravel layers with an upward-fining trend (Fig. 3c). The layers are up to 20 cm thick and are distinctly laminated ($T_b$) with a sharp erosional surface. They are commonly overlain by microripple, cross-laminated ($T_c$) medium sand and fine silt. In some cases, these cross-laminated sand divisions are occasionally overlain by the repetitive sequence of parallel-laminated very fine silt ($T_d$) (Fig. 3c). The sediments are composed largely of well-rounded volcaniclastic materials, containing greenish glass shard and pumice with a lesser amount (less than 40%) of terrigenous heavy minerals (Fig. 4e and f). SEM analysis for these deposits also shows neritic diatom species such as *Arachnoidiscus* sp., indicating the shallow-water origin of the sediments (Fig. 4e).

## Geochemical properties

Profiles of calcium carbonate, total organic carbon (TOC), and biogenic silica (BSi) are shown in Fig. 5 for two sedi-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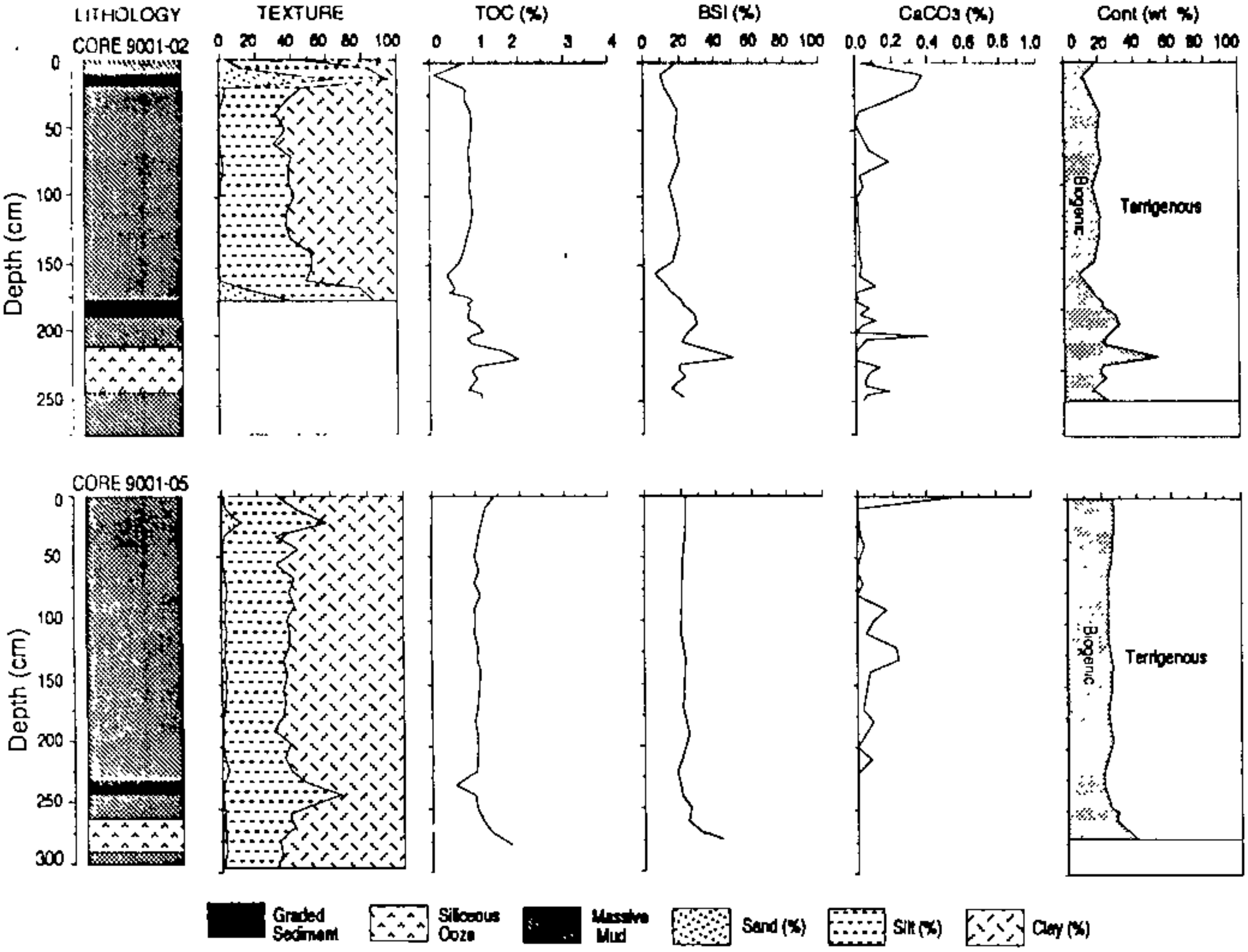


**Fig. 5** Downcore variations in lithology, grain texture, total organic carbon (TOC), biogenic silica (BSi), calcium carbonate ($CaCO_3$), and biogenic vs. terrigenous content for two representative cores. Note that all TOC and BSi profiles vary with sediment types, their values being highest in siliceous ooze. $CaCO_3$ contents are very low (less than 1%) throughout the cores

ment cores. Calcium carbonate contents are negligible (rarely exceeding 1%) and show no systematic downcore variation (Fig. 5). In core 9001-02 the measured $CaCO_3$ values range from 0.01% to 0.37% and in core 9001-05 from 0.01% to 0.59%. The highest carbonate content is noted near the top of the cores.

Total organic carbon contents of core 9001-02 range from 0.11% to 1.98%, with a mean value of 0.90%, and for 9001-05 from 0.45% to 1.45%, with a mean value of 1.0%. These values, slightly higher than the 0.2% in open sea sediments (Bordovskiy 1965), appear to be associated with typical Antarctic waters. Biogenic silica contents of core 9001-02 are in the range of 6.64–51.18%, with a mean value of 12.06%. For core 9001-05, the contents range from 18.08% to 33.19%, with a mean value of 14.22%. These values coincide, in general, with those of the 10–20% in surface sediments of the Bransfield Strait (Dunber et al. 1986; Singer 1987).

Both TOC and BSi typically vary by sediment type, regardless of core locations (Fig. 5): the lowest values correspond to graded sediment (0.44–0.45% TOC, 9.66–20.39% BSi); the intermediate values to massive muds (0.97–1.21% TOC, 14.38–24.58% BSi); and the highest values to siliceous ooze (1.42–1.98% TOC, 33.19–51.18% BSi).

◄

**Fig. 4** SEM micrographs of the sediment cores from King George Basin. **a** *Nitzschia kerguelensis* in the siliceous ooze of core 9001-02 (core depth, 222 cm); **b** *Rhizosolenia* sp. in the siliceous ooze of core 9001-02 (core depth, 208.5 cm); **c** *Chaetoceros* sp. in the siliceous ooze of core 9001-02 (core depth, 243.5 cm) – note intact frustule of *Chaetoceros* sp. in chain-form (up to 20 μm long); **d** fragmented diatoms and debris in the massive mud of core 9001-03 (core depth, 126 cm); **e** *Arachnoidiscus* sp. (neritic diatom) lying on a volcanic grain in graded sediment section of core 9001-02 (core depth, 11 cm); **f** A well rounded volcanic grain (lower left) in the graded sediment of core 9001-05 (core depth, 225 cm)

## Clay mineral distributions

The <2-μm clay minerals of core sections are, on the average, composed of 58% illite, 19% chlorite, and 19% smectite. Kaolinite rarely exceeds 1%. For most cores, concentrations of both illite and chlorite decrease slightly

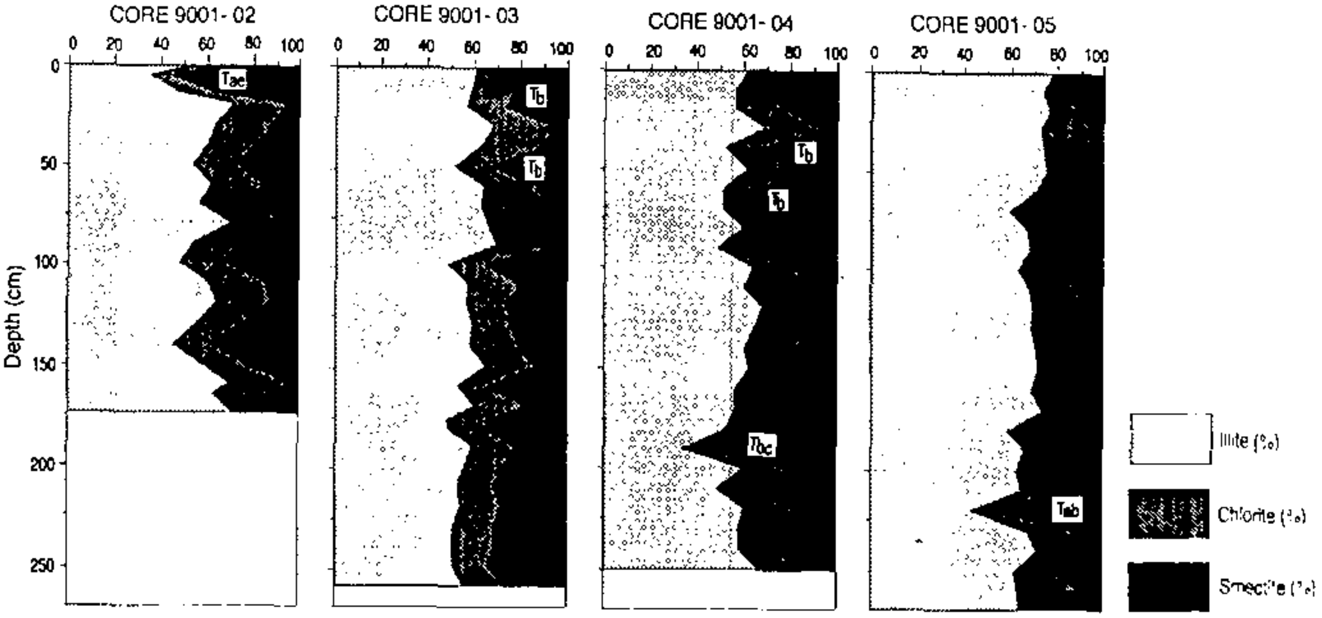


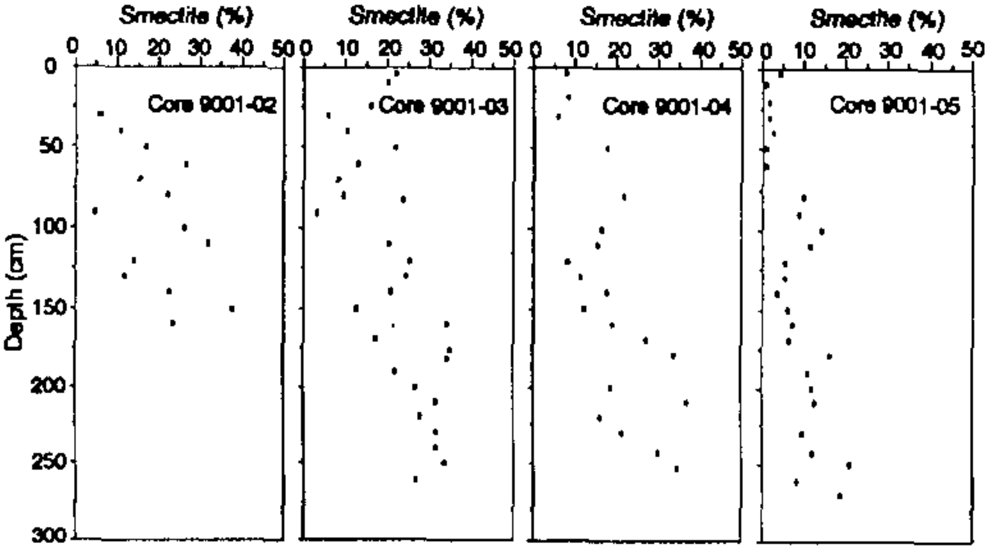
**Fig. 6** Profiles of clay mineral composition with depth. Note that, overall, the smectite content shows a decreasing trend upcore, except for graded sediment layers marked by T. Much higher smectite contents were consistently encountered in all graded layers (T) than in adjacent layers, suggesting their origin to be turbidite deposition derived from local submarine volcanoes

but systematically with core depth, from 78 to 54% and from 29 to 14%, respectively; some variations, however, occur in the graded sediment where they are relatively low (Fig. 6). On the other hand, the smectite content gradually increases downcore, from 1 to 31%, except for the graded unit where it is exceedingly high (more than 50%). In case the turbidite layers are excluded, such a downcore increase in smectite content is clearly shown in Fig. 7. Regionally, the smectite content is the highest near the Penguin and Bridgeman islands (9001-02) and gradually decreases southeastward (9001-05) (Figs. 1 and 6).

## Discussion

Among the many factors, high-surface water productivity and increased preservation rates under anoxic deep-water conditions are the dominant factors that would lead to prominent enrichment of organic carbon in marine sediments (Thiede and van Andel 1977). The latter condition, however, appears not to have been developed in the Bransfield Strait as indicated by the bioturbation that prevailed in late Holocene sediments of this area (Yoon et al. 1990). An organic carbon/sulfur diagram may also give information about depositional environments in terms of the oxic condition versus the suboxic to anoxic conditions (Fig. 8). For the Black Sea sediments, the positive interception of the regression line onto the axis of sulfur content coincides with the well-known anoxic bottom water of the sea (Hirst 1974). While plotting our sulfide-sulfur data from the King

*Fig. 7* Depth profiles of smectite content for sediment cores except for turbidite layers. Note that an upcore decreasing trend of smectite content becomes more evident than does the trend in Fig 6



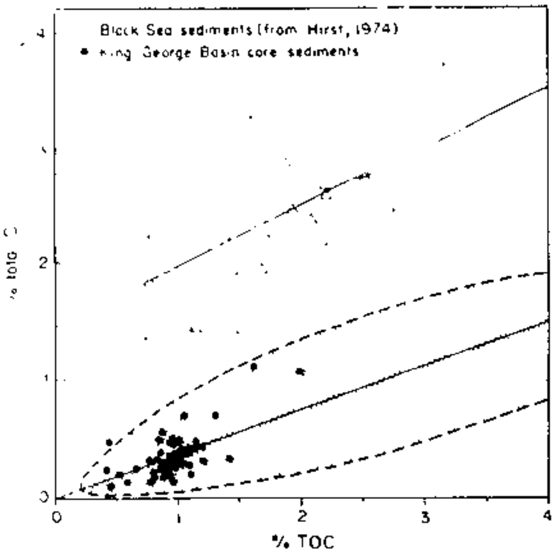


Fig. 8 Correlation between total organic carbon (TOC) and sulfide sulfur (total S) in sediment. The data from Black Sea cores are plotted to show them to be representative for anoxic sediments having an excess amount of sulfide sulfur as evidenced by the positive intercept of the regression line onto the axis of the sulfur content. The stippled area on the diagram represents a domain for the present-day normal oxic marine sediments (after Leventhal 1983) The plot of our data inside the lobe strongly suggests that anoxic bottom water conditions had not prevailed during accumulation of the King George Basin sediments

George Basin sediments, whose values range from 0.03% to 1.06%, the interception of the regression line onto the axis of sulfur content draws close to zero (Fig. 8), indicating that conditions of anoxic bottom water have not prevailed in the basin. Therefore, well-preserved laminations with high organic matter content in the siliceous ooze in the King George Basin appear to result from the rapid accumulation associated with increased paleoproductivity in the surface water rather than from development of an anoxic depositional environment.

Increased surface-water productivity occurs in open water close to the receding ice edges as a result of sea-ice melting and increased water column stability (Smith and Nelson 1985; Jordan and Pudsey 1992). These conditions produce large amounts of biogenic materials within a short time interval, allowing for mass sedimentation of diatom frustules by "marine snow" (Honjo et al. 1982; Smith and Nelson 1986). SEM photographs of the diatoms for the siliceous ooze indicate mass accumulation of diatoms, showing intact frustules of diatoms, typically *Rhizosolenia* sp. and *Chaetoceros* resting spores (Fig. 4b and c). In particular, sediment layers characterized by unusually high percentages of *Nitzschia* sp. (Fig. 4a) suggest diatom blooms related to the presence of shallow, mixed, and stratified meltwater near the receding sea-ice edges (Kang and Fryxell 1992). The considerable thickness (up to 30 cm) of the siliceous ooze layers, however, preferentially suggests accumulation by multievent diatom blooms rather than as a result of deposition from a single bloom. This unit probably reflects a multiyear period of markedly increased seasonal ice-edge bloom during which perennial sea ice might have developed more extensively with its edge persisting over the core sites.

In contrast, the massive muds, characterized by increasing proportions of terrigenous clastic materials and denser bioturbation, represent fine-grained sedimentation in open water settings during the period when only annual sea ice was present over the core sites. In consequence, seasonal contrasts in productivity are not reflected within the sediments. Some of these muds may represent sediment gravity flows similar to "massive unifites" described by Stanley (1981). However, if this unit is the distal equivalent of the volcaniclastic turbidites found in many places in the Bransfield Basin (Anderson and Molnia 1989), then it should be largely composed of volcanogenic muds, and resulting deposits should be distinct in their compositions and biogenic contents from other portions of the cores. However, no such obvious contrasts were recognized within the cores. The massive muds often include dark bands and patches with high contents of organic carbon and biogenic silica that are more indicative of short-term, episodic planktonic blooms.

The well-developed normal grading and partial Bouma sequences in the graded sediments are indicative of a gravity-controlled mechanism. Especially, the abundance of coarse-grained, lower division ($T_{bcd}$, $T_{bc}$ and $T_b$) of the Bouma sequence in the sediments suggests the fairly rapid emplacement of the sediments within a rather short distance by high-density turbidity currents. Their vertical successions cannot be correlated from core to core (Fig. 2), again indicating the importance of local transport events, particularly from nearby seamount sources. This kind of depositional process and sediment source would lead to the enrichment of smectite but the depletion of organic matter in the graded sediments (Figs. 5 and 6). Anderson and Molnia (1989) noted numerous graded volcaniclastic units at the foot of seamounts and volcanic islands in the Bransfield Basin, indicating the importance of the adjoining seamounts as sources of the dispersed volcanic materials. Sediment gravity flow through the troughs on the Antarctic Peninsula platform may be a possible cause for the graded units of the studied cores. The troughs, however, are filled with diatomaceous muds and oozes identical to those in the basin floor (Jeffers and Anderson 1990), indicating that, during interglacial periods, these troughs would not carry a significant amount of terrigenous sediment on the basin in the form of turbidite deposits. Downslope transport from the South Shetland Islands may be responsible for the graded sediments. However, the axial volcanic ridge, defined as a back-arc spreading center by Anderson and Molnia (1989), is likely to act as a barrier to the transport of volcanic materials from the north to the study area, and thus is probably not a source for the graded units.

Clay mineral analyses reveal that the smectite content decreases slightly upcore, except in the graded unit where the smectite content is exceedingly high due to the considerable proportion of volcaniclastic materials (Figs. 6 and 7). A clay mineral study in the Bransfield Strait (Yoon et al. 1992) reveals that the distribution pattern of smectite is closely associated with volcanic activity, showing enrichment of smectite in bottom sediments around the recent volcanic islands. Hence, the decreasing trend upcore typically (Fig. 7) may record the decreasing importance of volcanic activity through time. Similarly, high amounts of smectite near the Penguin and Bridgeman islands (core 9001-02) probably result from considerable submarine volcanic activity related to back-arc spreading around these islands (Saunders and Tarney 1982; Pelayo and Wien 1986) (Figs. 1 and 6); some hydrothermal activity and high heat flow are reported to be higher in the King George Basin compared to areas further to the south (Han 1987; Suess 1987).

## Summary

Our study on the depositional environment of near-surface sediments from the King George Basin is summarized as follows:

1. Siliceous ooze containing relatively high concentrations of organic matter is interpreted as having been accumulated by mass sedimentation of diatom frustules; large blooms occurred in open water near the receding ice edge when multiyear ice had persistently existed over the core sites so that repetitive diatom blooms resulted in this unit.
2. Massive muds, characterized by slightly decreased TOC and BSi contents, represent hemipelagic sedimentation in the open water as found in the present Bransfield Strait where the biogenic sedimentation rate would be much lower than in the perennial setting of the ice edge under which the siliceous ooze units would have accumulated.
3. Graded sediments that include well-rounded volcanogenic grains and neritic diatoms (*Arachnoidiscus* sp.) were most probably derived from nearby seamounts by turbidity currents. This depositional process would result in the enrichment of smectite but the depletion of organic matter.
4. The vertical distribution of smectite content reveals a slight, but systematic, decrease upcore. This records the diminution of volcanic activity through time. Around the Penguin and Bridgeman islands, active volcanic and hydrothermal activities, related to back-arc spreading, have resulted in smectite enrichment in the sediments (core 9001-02) near those islands.

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