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Reconstruction of postglacial paleoproductivity in Long Lake, King George Island, West Antarctica

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Abstract: A sediment core (LS-1) collected from Long Lake in King George Island, South Shetland Islands (West Antarctica) was analyzed for a variety of textural, geochemical, isotopic and paleontological properties together with ^{14}C age dates. These data combined with published records of other studies provide a detailed history of local/regional postglacial paleoproductivity variation with respect to terrestrial paleoclimate change. The lithologic contrast of a lower diamicton and an upper fine-grained sediment demonstrates glacial recession and subsequent lake formation. The upper fine-grained deposit, intercalated by mid-Holocene tephra-fallout followed by a tephra gravity flow, was formed in a lacustrine environment. Low total organic carbon (TOC) and biogenic silica (Si_{bio}) contents with high C/N ratios characterize the diamicton, whereas an increase of TOC and Si_{bio} contents characterize the postglacial lacustrine fine-grained sediments, which are dated at *c.* 4000 yrBP. More notable are the distinct TOC maxima, which may imply enhanced primary productivity during warm periods. Changes in Si_{bio} content and $\delta^{13}C$ values, which support the increasing paleoproductivity, are in sympathy with these organic matter variations. The uniform and low TOC contents that are decoupled by Si_{bio} contents are attributed to the tephra gravity flows during the evolution of the lake rather than a reduced paleoproductivity. A very recent TOC maximum is also characterized by high Si_{bio} content and $\delta^{13}C$ values, clearly indicating increased paleoproductivity consequent upon gradual warming across King George Island. Comparable with changes in sediment geochemistry, the occurrence and abundance of several diatom species corroborate the paleoproductivity variations together with the lithologic development. However, the paleoclimatic signature in local terrestrial lake environment during the postglacial period (for example the Long Lake) seems to be less distinct, as compared to the marine environment.

Key words: Antarctica, lake sediment, paleoclimate, diatoms, organic carbon, carbon isotopes.

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Introduction

In order to understand the peripheral extension and retreat of continental glaciers during the late Quaternary (*e.g.* Domack *et al*. 2000), a variety of investigations have been conducted to the Antarctic Ocean and its marginal regions. The advance and retreat of widespread permanent glaciers are the major feature of global climate variability in the polar region. Thus, the extensive bathymetric surveys which have identified these glacial features have enabled us to elucidate the postglacial evolution in the continental shelves around the Antarctic Peninsula (Pudsey and Camerlenghi 1998). Further, multi-disciplinary approaches to the study of marine sediments have provided considerable evidence for significant Holocene climatic changes (Leventer *et al*. 1993; Domack *et al*. 1995; Rathburn *et al*. 1997; Kirby *et al*. 1998; Yoon *et al*. 2000; Khim *et al*. 2001; Taylor *et al*. 2001). These results were consolidated by the identification of paleoclimatic changes, which have controlled terrestrial lake sedimentation (Birnie 1990; Schmidt *et al*. 1990; Appleby *et al*. 1995; Björck *et al*. 1991c, 1993, 1996; Jones *et al*. 1993, 2000; Roberts *et al*. 2001; Tatur *et al*. 2004).

There is a great potential for the lake sediments in maritime Antarctic to provide important data for paleoenvironmental reconstruction. Conformable Holocene sequences have been found from numerous sites along the Antarctic Peninsula and from outcrops and lakes in the nearby islands (John 1972; Holdgate 1977; Mäusbacher *et al*. 1989; Schmidt *et al*. 1990; Ingolfsson *et al*. 1992, 1998; Björck *et al*. 1993, 1996; Fulford-Smith and Sikes 1996; Yang and Harwood 1997; Tatur *et al*. 1999). Being only under the limited impact of human activity, lake sediments from maritime Antarctic have been especially useful in the elucidation of climate impact during the Holocene (Birnie 1990; Fulford-Smith and Sikes 1996; Jones *et al*. 1993, 2000; Roberts *et al*. 2001). Many lake sediment sites from islands such as Livingstone (Björck *et al*. 1991c) and James Ross (Ingolfsson *et al*. 1992; Björck *et al*. 1996) have been investigated using a multi-disciplinary approaches with the main focus on freshwater diatoms (Mäusbacher *et al*. 1989; Schmidt *et al*. 1990; Fulford-Smith and Sikes 1996; Yang and Harwood 1997; Tatur *et al*. 1999; Jones *et al*. 2000). Integrated with glacial stratigraphic and geomorphologic results, the contrasting climatic stages (arid and cold *vs.* humid and warm) have been reconstructed *vis-à-vis* the marine climate variation.

The Holocene environmental history of the South Shetland Islands has been controversial owing to few and insufficient data. John (1972) and Sudgen and Clapperton (1986) suggested that the deglaciation generally commenced shortly before 10 kaBP in the South Shetland Islands. The latter reported that the extensive glaciers in the South Shetland Islands were developed at about 9.5 kaBP. In contrast, Mäusbacher *et al*. (1989) demonstrated that somewhat later deglaciation with the present-day warm environment dated back to between 9 and 5 kaBP on King George Island, supported by Martinez-Macchiavello *et al*. (1996). Subsequently, Björck *et al*. (1993) documented that a climatic optimum with mild and humid conditions occurred between 3.2 and 2.7 kaBP, which triggered a glacial re-advance. Similarly, Schmidt *et al*. (1990) reported that an allochthonous input (*i.e*. tephra-fallout) increased between 4.7 and 3.2 kaBP on King George Island.

We have subjected a radiometrically-dated core (LS-1) obtained from Long Lake to various lithologic, geochemical, isotopic, and paleontological interpretations. These permit the reconstruction of postglacial paleoproductivity in King George Island and, in turn, to the terrestrial paleoclimatic evolution of that area.

Material and methods

The Long Lake (also known as Dlinnoye Ozero, Długie Jezioro, Langer See or Yanou/Hihu Lake), near the Chinese *Great Wall* Station on Fildes Peninsula, King George Island, lies in an abandoned melt-water channel, behind a raised beach, 12 m above sea level (Fig. 1). A 7.5-m long core (core LS-1) was obtained from the lake with logistic support from Chinese scientists. The continuous core was sub-

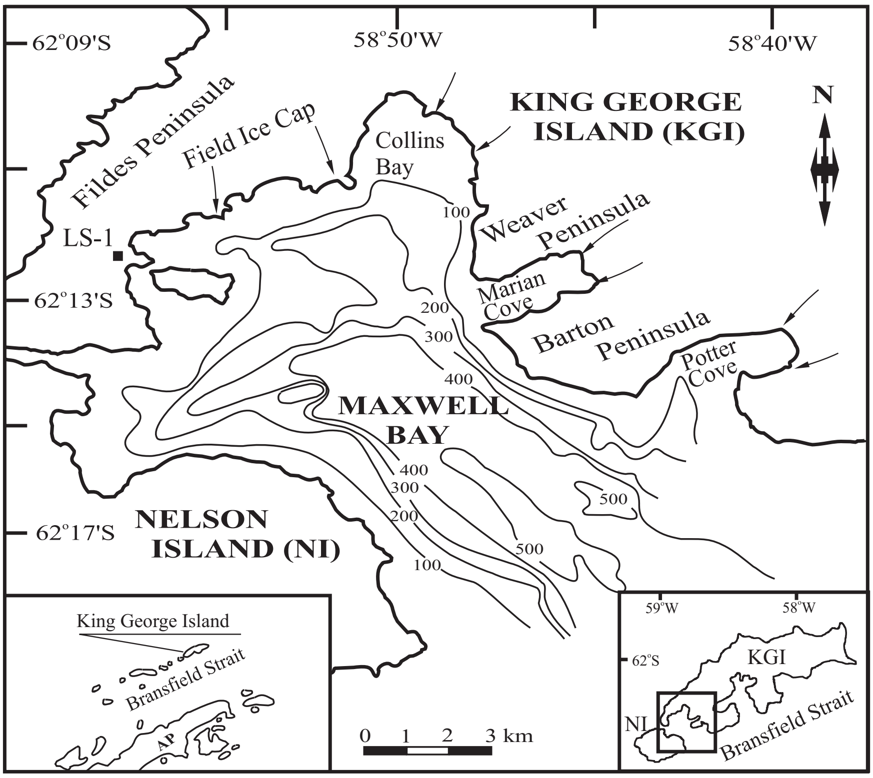


Fig. 1. Study area and location of sediment core LS-1 in Long Lake in King George Island, South Shetland Islands, West Antarctica.

jected to laboratory analysis. It was cut in half and one side was used for X-ray radiography. Owing to the small diameter of core, sub-samples were collected from the remaining half, after measurement of magnetic susceptibility.

Magnetic susceptibility was measured using a Bartington MS-2C magnetic susceptibility sensor, scanning at 1 cm interval with a portable point sensor. For grain size analysis, grains larger than 63 μm (gravel and sand) were separated by wet sieving and classified by dry sieving. Grains smaller than 63 μm (silt and clay) were analyzed for grain-size distribution using a Micrometrics Sedigraph 5100D.

Sub-samples were freeze-dried and grounded by agate mortar for geochemical analysis. Total carbon (TC) and total nitrogen (TN) contents were measured using a Carlo-Erba NA-1500 Elemental Analyzer. The precisions for TC and TN calculations were ±0.4% and ±0.1%, respectively. Total inorganic carbon (TIC) content was analyzed by UIC coulorometry (CM 5130) with a precision of ±0.1%. The $CaCO_3$ content was calculated by multiplying TIC by 8.333. Total organic carbon (TOC) content was obtained from the difference between TC and TIC.

Aliquots of calcium carbonate-free dried samples were sent to University of California, Davies for $\delta^{13}C$ analysis. Capsules containing about 15 mg of acid-treated sediment powder were placed in the EUROPA-INTEGRA-CN Analyzer. Combustion gases, burned at about 1100°C, were conducted through a reduction column and the separated CO_2 gas stream then entered into a mass spectrometer for analysis. Carbon isotope ratios in sediment organic matter are expressed in conventional delta (δ) notation, which is the per mil (‰) deviation from the Vienna PeeDee Belemnite (VPDB). The precision for carbon isotope was ±1‰.

Biogenic silica (Si_{bio}) content was analyzed by wet alkaline extraction, modified from Mortlock and Froelich (1989) and Müller and Schneider (1993). Approximately 10 mg of sediment powder in a 50 ml polypropylene tube were dissolved using *c.* 30 ml of a 1N NaOH solution. While the tubes were placed in a drying oven at 85°C for 5 hours, a 0.1 ml solution was taken into 10 ml vial tube containing 2 ml 0.1N HCl at every hour. The dissolved silica was measured on diluted samples using a molybdate blue spectrophotometric method. Duplicate measurements were conducted on each sample. The relative error of Si_{bio} content in sediment samples was less than 1%.

The size range of diatoms is considerable variable (5 to 150 μm) and the nature and grain size of other sediment components also vary greatly. This has made it difficult to apply standard diatom separation techniques (Schrader 1974) without loss of some size fractions. A small quantity of sediment was taken at 10 cm intervals from both cores. The wet sediments were placed in a 200 ml beaker of 15% hydrogen peroxide solution and left to stand for 24 hours. The supernatant liquid was poured off and then distilled water was added to the residue, such that the sample was made up to 100 ml and homogenized in an ultrasonic device. Using a micropipette, 0.5 ml of this solution was placed on a cover glass, dried upon a hot plate at 60°C and then mounted in Pleurax on glass slides. All diatoms were identi-

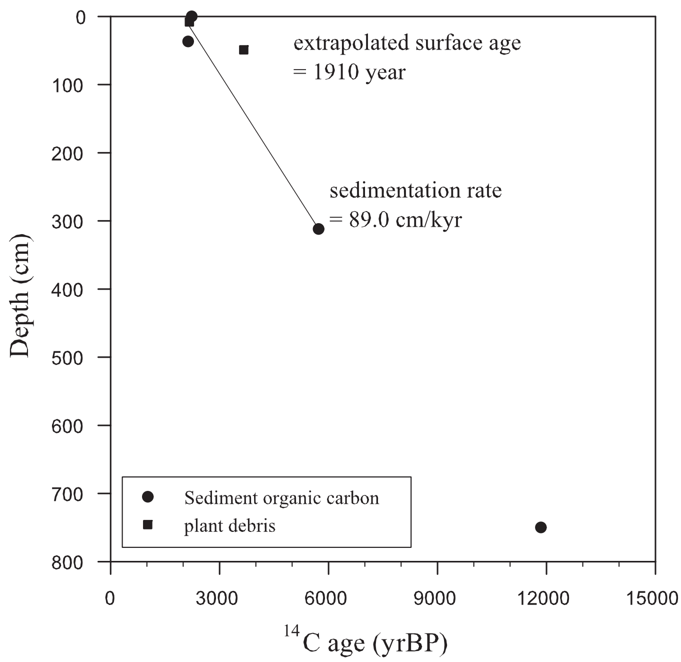


Fig. 2. Age-depth relationship showing the apparent sedimentation rate.

fied and counted until the number of individual specimens totalled 400. Specimens larger than half of a valve were counted as 1; for pinnate diatoms, each pole was counted as 1/2. Counts were converted to percentage of total assemblage.

Accelerator mass spectrometry (AMS) radiocarbon (^{14}C) ages were measured at Institute of Geological and Nuclear Sciences (New Zealand). Owing to the lack of carbonate fossils, the acid-insoluble organic matter fraction of bulk sediments and some plant fragments were used.

Results

The ^{14}C age dates of sediment organic carbon and plant debris are summarized in Table 1. Radiocarbon ages are somewhat scattered, and some age reversal with depth seems to have occurred as expected (Fig. 2). There is no systematic pattern or offset of radiocarbon ages between sediment organic carbon and plant debris (Table 1). The uncorrected surface age of the uppermost part of core-top LS-1 is 2232 yrBP. Such an old age seems to be due to the terrestrially-sourced old carbon being assimilated in organic production (Björck *et al*. 1991b; Gibson *et al*. 1999). The age/depth relationship shows no significant variation in the sedimentation rate, possibly due to the paucity of data. A linear sedimentation rate was calculated by interpolation between the dated levels which covered only the fine-grained sed-

Table 1

Radiocarbon dating ages of core LS-1

Sample ID	Sample depth (cm)	Material	$\delta^{13}C$ (‰)	^{14}C age (yrBP)	Lab code
AJ-1	0	bulk sediment	–17.54	2232±55	NZA13399
GA-6a	8	plant	–26.47	2169±45	NZA19621
AJ-2	37	bulk sediment	–22.28	2133±60	NZA13543
GA-6b	49	plant	–25.04	3667±45	NZA19623
AJ-3	312	bulk sediment	–22.88	5723±70	NZA13465
AJ-4	757	bulk sediment	–27.74	11848±80	NZA13602

iments, although the sedimentation rate may vary during deposition. However, in this context, the apparent linear sedimentation rate of 89.0 cm/kyr during the Holocene lies well within the range of the values reported from terrestrial environments (Mäusbacher *et al*. 1989; Schmidt *et al*. 1990; Yang and Harwood 1997), and upward extrapolation of the linear sedimentation rate results in an assumed core-top age of about 1910 yrBP (Fig. 2). This supports the notion that the older ages of the lacustrine surface sediments are attributed to significant inputs of older carbon from sedimentary rocks. Alternatively, the possibility of the loss of the core-top portion during the coring cannot be ruled out entirely. Nevertheless, the modified chronology using the acceptable measured ages shows that the LS-1 sediments represent approximately the entire postglacial period of the Holocene.

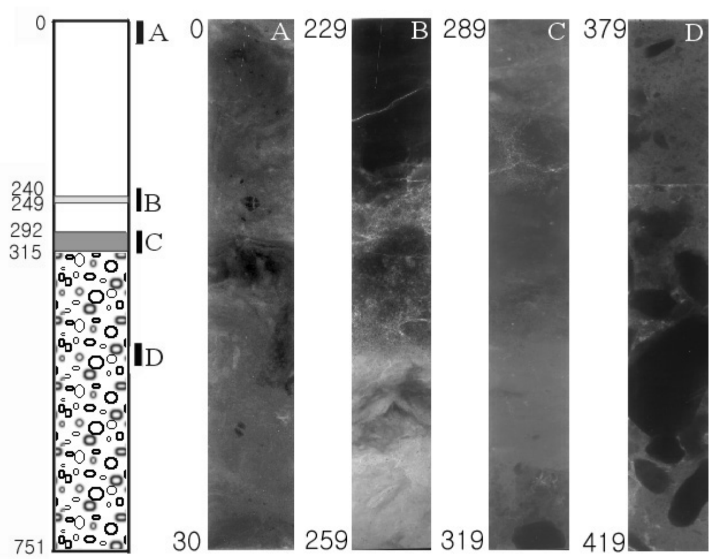


Fig. 3. Schematic lithostratigraphy with some examples of X-radiography showing the overall feature of sediment lithology.

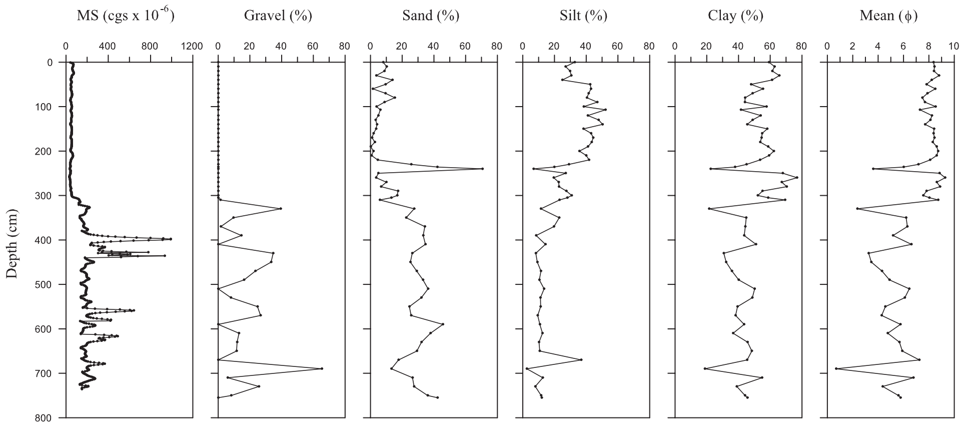


Fig. 4. Downcore variation of magnetic susceptibility, gravel content, sand content, silt content, clay content, and mean grain size of the core sediment LS-1.

The core LS-1 was divided into two major parts, based on textural contrast and X-radiography (Fig. 3). The upper part (*c*. 300 cm in thickness) comprises fine-grained silt and clay with little sand content, whereas the lower consists of mixed gravel, sand, and clay typical of a diamicton (Fig. 4). The lower diamicton is massive, clast-supported, and very poorly sorted. This unit corresponds genetically to the argillaceous fluvioglacial deposit formed before 6 kaBP, as defined by Tatur *et al*. (2004). The upper argillaceous sediments are characterized by intense bioturbation and abundant moss remains and may be subdivided into three units (lacustrine, pyroclastic, and lacustrine in upward order). The lower lacustrine unit consists of a poorly laminated clay gyttja, containing submerged moss detritus. The upper lacustrine unit is very similar. These two clay gyttjas are separated by a reworked tephra-fallout which was washed down from the catchment area into the lake by gravity flow at *c*. 4–5 kaBP (apparent age) (Tatur *et al*. 2004). The tephra and reworked tephra layer is 1.5 m thick. Presumably all these tephra horizons were derived from the Deception Island volcano (Björck *et al*. 1991a).

Magnetic susceptibility (MS) tests amply differentiate these lithologies; the upper part of core generally shows the low MS signal (<100 cgs), whereas the lower diamicton has large fluctuations (between 200 and 1000 cgs; Fig. 4). The MS intensity is controlled by the proportion of magnetic minerals within the sediments (Karlin 1990). The relatively large quantity of gravel and sand in the lower part is associated with an increase of MS intensity (Fig. 4). The greater the proportion of gravel, the higher the MS reading. The fluctuation of gravel content in the lower part of the core may reflect an advance and retreat of the ground ice during the glacial period (Clapperton and Sudgen 1982; Clapperton *et al*. 1989). The uniform mean grain size and low MS intensity in the upper part of core correspond with the pyroclastic unit composed of reworked tephra-fallout and two clay gyttja layers.

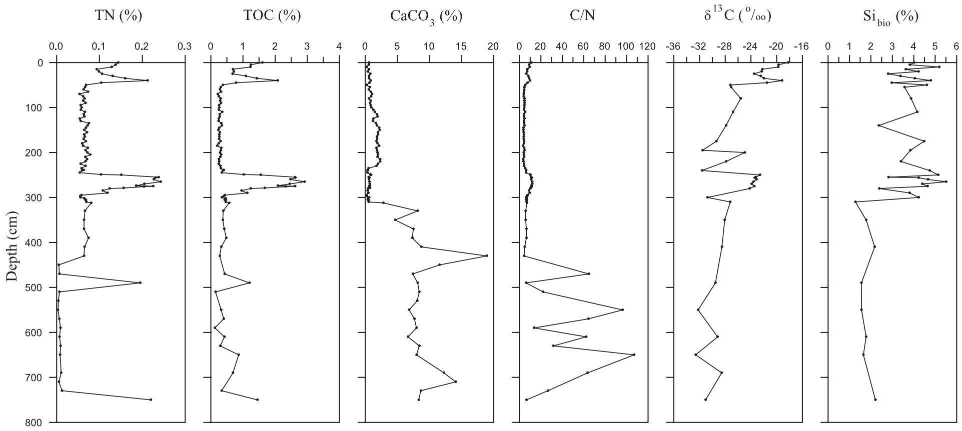


Fig. 5. Downcore variation of total nitrogen (TN) content, total organic carbon (TOC) content, calcium carbonate ($CaCO_3$) content, C/N ratio value, $\delta^{13}C$ values of sediment organic carbon, and biogenic silica (Si_{bio}) content of the core sediment LS-1.

Variations in the geochemical properties of core LS-1 sediments reflect both the lithologic differentiation and the MS properties (Fig. 5). The total nitrogen (TN) and total organic carbon (TOC) contents show a similar variation, characterized by much higher values in the upper part. By contrast, the variation patterns of $CaCO_3$ contents and C/N (TOC/TN) ratios exhibit converse relationship with that of TOC and TN contents. Two high TOC peaks in the upper part correspond to the two clay gyttja units, both of which are separated by a tephra-fallout layer characterized by a modest TOC content (*c.* 0.3%). A comparable parallel variation between TN and TOC reflects a common source, which is likely to be organic carbon and nitrogen. However, the high C/N ratio in the lower part may be due either to the selective degradation of organic nitrogen (Kemp *et al.* 1977) or to a different source of terrestrial plants (diatoms or mosses) (Mäusbacher *et al.* 1989). The two distinct TN and TOC peaks in the upper part (at 40 and 270 cm) may indicate an enhanced production of organic matter, or simply the better preservation or moss detritus.

The $\delta^{13}C$ values of sedimentary organic matter also reflect the lithologic development; these changes are parallel to those in the geochemical properties (Fig. 5). Upward and gradual increases of $\delta^{13}C$ values were observed in the upper part of core, closely following the TOC variations. The two prominent peaks between 200 and 300 cm and from 40 cm to the core-top surface correspond with the two clay gyttja layers, as did the TOC contents (Fig. 5). However, the intermittent tephra layer shows that most of the $\delta^{13}C$ values are less than –28‰. The highest $\delta^{13}C$ values occurred in the uppermost part of the core, showing more than –20‰. In general, because high internal carbon demands by rapid carbon fixation may cause isotopic disequilibria in and/or around the cells, high productivity is linked to ^{13}C enrichments in phytoplankton carbon, thereby reducing the magni-

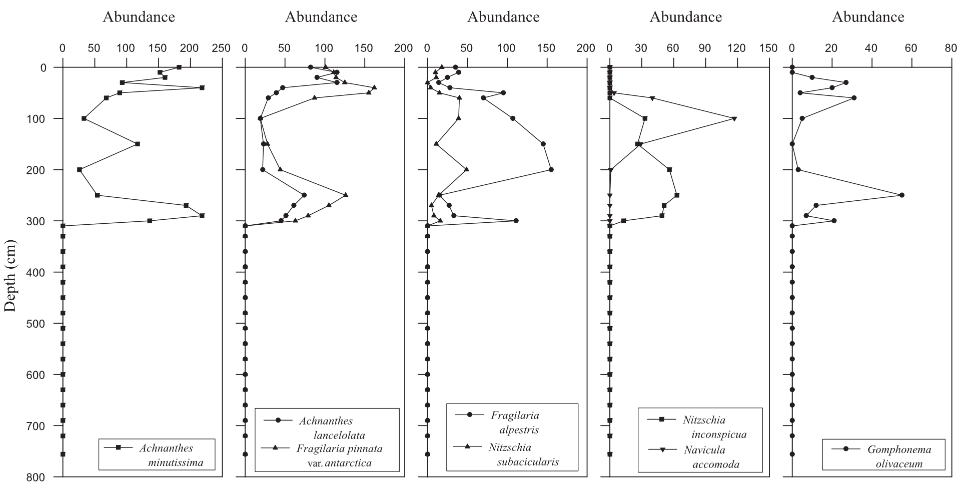


Fig. 6. Downcore variation of diatom abundance of species *Achnanthes minutissima*, *Achnanthes lancelolata*, *Fragilaria pinnata* var. *antarctica*, *Fragilaria aplestris*, *Nitzschia subacicularis*, *Nitzschia inconspicua*, *Navicula accomoda*, and *Gomphonema olivaceum*.

tude of the isotopic fractionation (O'Leary 1981). Thus, the intervals of high $\delta^{13}C$ values in the upper part of core may reflect the enhanced primary production periods. The close similarity in patterns between $\delta^{13}C$ value and Si_{bio} content, the latter of which is mainly controlled by the diatom content, is striking (Fig. 5). At first approximation, the geochemical and isotopic properties are likely to reflect the degree of lacustrine paleoproductivity during the postglacial period which is directly controlled by climatic conditions.

Tatur *et al*. (1999) reported that diatom assemblages in lake sediments should be ideal indicators of environmental changes. In the case of core LS-1 sediments, freshwater diatom analyses show that, among forty-eight sediment samples, fifty-seven species belonging to fourteen genera are present. Certainly, some representative species appear to be closely associated with variations of geochemical properties (Fig. 6). The introduction of diatoms seems to follow one or other of two pathways. One seems to follow the TOC variation, whereas the other is in converse relationship with the TOC variation. Representation of *Achnanthes minutissima, A. lancelolata, Fragilaria pinnata* var. *antarctica*, and *Gomphonema olivaceum* in the flora is closely associated with the TOC variations. The first three species are dominant. By contrast, *Fragilaria alpestris*, *Nitzschia subacicularis, N. inconspicua,* and *Navicula accomoda* appear in converse relationship with TOC representation. Thus, lake biodiversity in terms of diatom assemblages seems also to be influenced by the lithologic development during terrestrial paleoclimatic evolution. In particular, since lake formation, a notable reduction in the diatom population is clearly attributable to a sudden tephra-fallout (Björck *et al*. 1991a). As explained previously, the recovery of an assemblage in the lake corresponds to the change of clastics to gyttja sediments. However, it is important to note that the diatom species composition of uppermost gyttja assemblage is quite different from that of lower gyttja.

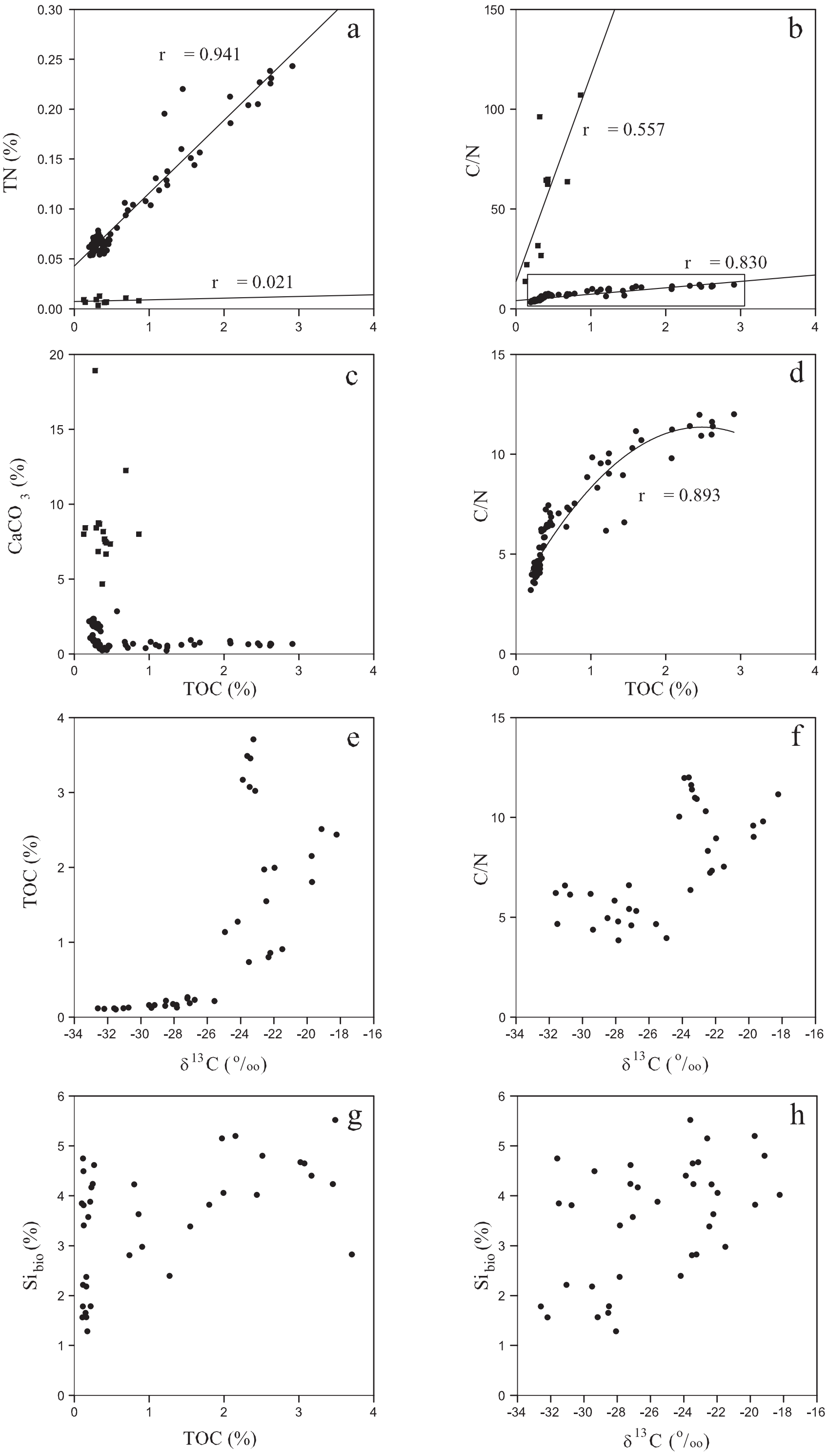
Discussion

Massive diamictons (basal tills) in terrestrial environments may form during the advance of mountain glaciers into a glacier-influenced lake environment (John 1972; Clapperton and Sudgen 1982; Sudgen and Clapperton 1986). The thick massive diamicton deposit in the lower part of core LS-1 is clearly devoid of diatom valves (Fig. 6), indicating that the grounded glaciers had been persisted in the core site before the formation of postglacial lake environment at *c*. 4 kaBP (Fig. 7). Such a consideration is supported by Mäusbacher *et al*. (1989), who calculated that in King George Island the major deglaciation and the initiation of a limnic environment occurred between 5.5 and 5.0 kaBP. Since the deglaciation, the fine-grained sediments of late Holocene age were deposited from the supply of meltwater derived from the retreating glacier margin. Thus, the introduction of fine-grained sediments into the lake indicates the onset of warm conditions.

Deposition of fine-grained sediments in Long Lake is identified by the magnetic susceptibility (MS) intensity measurement (Fig. 4). The MS variations may be due to either diagenetic dissolution of magnetite with depth or iron-sulfur diagenesis controlled by higher organic carbon content at times of increased productivity (Thompson and Oldfield 1986). We suggest that the marked MS attenuation in the upper part of the LS-1 core is mainly attributable to the degree of preservation of magnetic minerals (Fig. 4). The sudden introduction of tephra-fallout and reworked tephra to the lake caused the low and uniformly attenuated signal in the upper part of the core. Apart from this tephra layer, the relatively low MS in the upper part may, thus, reflect the warm period which was particularly favorable for the deposition of fine-grained sediments (Fig. 4). Likewise, the productivity cycles recognized in the marine sediment cores around the Antarctic Peninsula region result in the coeval MS fluctuations (Taylor *et al*. 2001; Khim *et al*. 2002). In general, the low MS values correspond to high biological production periods, which are in turn characterized by a dominance of fine-grained sediments during warm periods.

A comparable variation of TN and TOC contents in the core implies that the carbon and nitrogen in the sediments were derived largely from the same source (Fig. 7). Such a condition may be substantiated by their linear correlations. With respect to the correlations between TN and TOC contents, the organic matter

Fig. 7. Relationships between (a) total nitrogen (TN) content and total organic carbon (TOC) content, (b) C/N ratio and TOC content, (c) $CaCO_3$ and TOC content, (d) C/N ratio and TOC content (enlargement of inset box in (b)), (e) TOC content and $\delta^{13}C$ values of sediment organic carbon, (f) C/N ratio and $\delta^{13}C$ values, (g) biogenic silica (Si_{bio}) content and TOC content, (h) Si_{bio} content and $\delta^{13}C$ values of sediment organic carbon. →



a
r = 0.941
r = 0.021
TN (%)
b
r = 0.557
r = 0.830
C/N
c
CaCO 3 (%)
TOC (%)
d
r = 0.893
C/N
TOC (%)
e
TOC (%)
δ13C (‰)
f
C/N
δ13C (‰)
g
Sibio (%)
TOC (%)
h
Sibio (%)
δ13C (‰)

seems to be differentiated by two clusters; high TN closely correlates ($r^2 = 0.941$) with TOC, although low TN correlates poorly ($r^2 = 0.021$) with the TOC contents (Fig. 7a). These two distinct clusters can be also identified from the relationship between the C/N ratio and TOC values (Fig. 7b). A separate cluster of low TOC content and high C/N ratios are present in the diamicton (Fig. 5). During the deposition of the diamicton, biological production seemed to be limited; diatom valves were sparse and most organic matter was apparently derived from the nearby terrestrial environment. Also, the low TN content in the diamicton may be due to the selective degradation of terrestrial organic nitrogen (Kemp *et al*. 1977).

Another cluster characterized by high TN values shows a strong linear correlation ($r^2 = 0.941$) with respect to TOC content. This may signify that the nitrogen and carbon originate from the organic matter autochthonous to lake environment (Fig. 7a). However, in respect of the relationship between the C/N ratio and TOC content (Fig. 7d), there seems to be some selective degradation of organic nitrogen in the upper part of core, which has resulted in the wide range of C/N ratios. In general, the organic matter produced in the terrestrial environment shows that C/N ratios are higher than 7 (Kemp *et al*. 1977). The low C/N ratio (*c*. 5) in the fine-grained sediments is attributable, not so much to the selective degradation of the carbon but to the absorption of ammonia into the clay particles (Stevenson and Cheng 1972). Therefore, the high TOC value in the upper part of core clearly indicates an enhanced biological productivity. In the lower part of core, low TOC samples correspond with high $CaCO_3$ contents (Fig. 7C); this indicates that the biological productivity was not induced by carbonate production.

The relationship between TOC content and $\delta^{13}C$ of organic matter also explains the two separate clusters already noted in respect of the TOC and TN contents (Fig. 7e). The low TOC contents correspond to the relatively low $\delta^{13}C$ values less than –26‰, whereas the high TOC values are related to high $\delta^{13}C$ values (–25 to –18‰). Similar differentiation was observed in the relationship between C/N ratio and $\delta^{13}C$ values (Fig. 7f). The $\delta^{13}C$ values of organic particles depend mainly on changes in the ambient temperature, on the type of autotrophic species, or on the number of degradation processes. Because in the case of phytoplankton assimilation the carbon isotopic fractionation is influenced by the ambient concentration of carbon dioxide molecules, the $\delta^{13}C$ values of organic matter may reflect the $[CO_2]_{aq}$ concentration changes in surface water.

The low $\delta^{13}C$ values may be explained by effects on C-fixation processes at low temperature and the related high CO_2 availability to phytoplankton. Rau *et al*. (1997) suggested that because of low water temperatures the very low $\delta^{13}C$ values of Antarctic phytoplankton result from high $[CO_2]_{aq}$ concentrations. Similarly, Wada *et al*. (1987) demonstrated that the low isotopic compositions of Antarctic phytoplankton were probably caused by a high pCO_2 in the surface waters and slow growth rates under low light intensities. In general, high productivity is linked to ^{13}C enrichments in phytoplankton carbon because high internal carbon

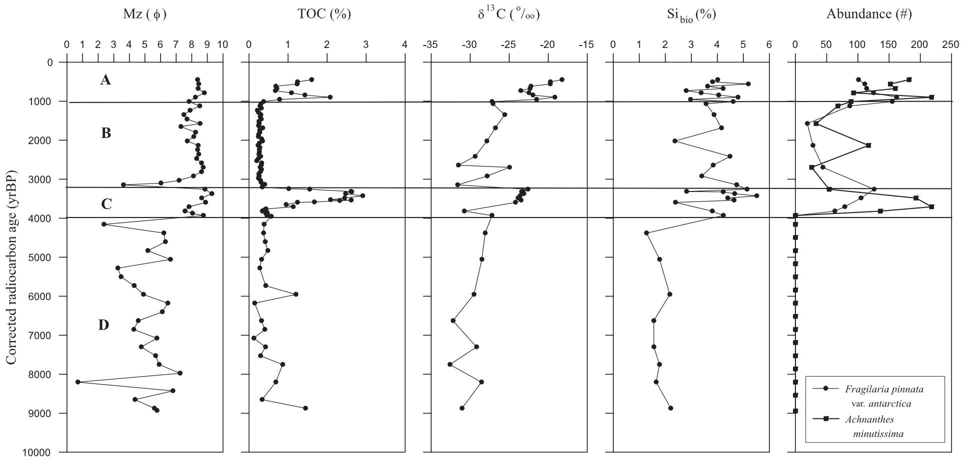


Fig. 8. Chronological variation of mean grain size, total organic carbon (TOC) content, $\delta^{13}C$ values of sediment organic carbon, biogenic silica (Si_{bio}) content, and diatom abundances of *Achnanthes minutissima* and *Fragilaria pinnata* var. *antarctica*.

demands by rapid carbon fixation may cause isotopic disequilibria in and/or around the cells, reducing the magnitude of the isotopic fractionation (O'Leary 1981). Thus, the cluster representing high TOC content and high $\delta^{13}C$ values clearly indicates the enhanced productivity during the postglacial period. In addition, the high C/N ratios with high $\delta^{13}C$ values are typical of terrestrial organic matter production.

In general, the biological productivity in lake sediments in the Antarctic region is characterized by diatom production (Birnie 1990; Fulford-Smith and Sikes 1996; Jones *et al*. 2000; Roberts *et al*. 2001). Many lake sediments in King George Island are also rich in diatoms (Mäusbacher *et al*. 1989; Schmidt *et al*. 1990; Yang and Harwood 1997). In Long Lake, high TOC contents in the upper part of core are attributable to the diatom abundance (Fig. 6). The correlation between TOC and Si_{bio} contents generally indicates a positive relationship although these are numerous instances where no relationship can be demonstrated (Fig. 7g). However, the relationship between Si_{bio} content and $\delta^{13}C$ values emphasizes the universal direct correlation (Fig. 7h), demonstrating that high Si_{bio} production leads to the increasing $\delta^{13}C$ values (O'Leary 1981).

At first approximation, the degree of paleoproductivity in Long Lake can be estimated qualitatively by the measured parameters taken in chronological sequence (Fig. 8). Prior to *c*. 4 kaBP when the lake formation is likely to have originated, most of values are quite uniformly low, indicating that the productivity during stage D was early modest. During this period, the thick massive diamicton deposit, clearly devoid of diatom valves (Fig. 6), indicates that the grounded glaciers had persisted at the core site before the formation of the postglacial lake environment. This conclusion is supported by that of Mäusbacher *et al*. (1989), *i.e* that major deglaciation and initiation of a limnic environment occurred between 5.5 and 5.0 kaBP in King George Island.

At the initial stage of lake formation (stage C), an abrupt increase of geochemical, isotopic, and paleontological parameters implies that conditions favorable for enhanced productivity had probably been established (Mäusbacher *et al*. 1989; Schmidt *et al*. 1990; Yang and Harwood 1997). During this interval, as the lake formed at the front of retreating glacier, a lacustrine ecosystem commenced to develop. Afterwards, the retreating glacier front receded to move its recent position, and a lacustrine ecosystem has evolved in a placid lake environment, supplied mainly by the surface runoff from a restricted catchment.

Low TOC and relatively lower diatom distribution are characteristic of stage B. Then, low preservation of TOC with uniformly low diatom production variation of TOC contents are directly associated with the tephra-fallout following the eruption of Deception Island volcano which shocked the lake biota (Björck *et al*. 1991a). About one and half meters of the volcanic ash was deposited. The lake eventually returned to the placid lacustrine environment which has persisted to the present time. During the last 1000 years of stage A, TOC and other properties have again increased up to a level comparable to those of stage C. Such recurrence seems to be indicative of the recent atmospheric warming, leading to an enhanced paleoproductivity.

The climatic optimum in the Antarctic region seems to be a general phenomenon, although it is expressed in slightly differing ways (Fig. 9). Nothing very dramatic in paleoclimatic evolution has been noted on King George Island (Mäusbacher *et al*. 1989). However, the high TOC, Si_{bio}, $\delta^{13}C$ values and abundant diatoms in the core LS-1 (at 250–300 cm; Fig. 7), demarcated by strong peaks, undoubtedly indicate an increased primary productivity at the time of the initiation of Long Lake. The correspondence between the different South Shetland Islands records for the last 5000 years is also fairly good (Fig. 9; Mäusbacher *et al*. 1989; Schmidt *et al*. 1990; Björck *et al*. 1993). The invariable and uniform parameters from 50 to 250 cm represent the tephra-fallout period, which might reasonably be considered a force for change in respect of the biota of lakes on King George Island. However, this mid-Holocene period of tephra sedimentation correlates exactly with either a cessation of deglaciation, a wetter climate or even a glacial advance inferred from other lakes in the area (Mäusbacher *et al*. 1989; Schmidt *et al*. 1990; Ingolfsson *et al*. 1992; Hjort *et al*. 1997). This climatic event seems to be regionally important, which means that paleoenvironmental signals from tephra-fallout and climate change overlap each other in the lake sediment record. The reappearance of an increasing trend of TOC, Si_{bio}, $\delta^{13}C$ and diatom abundance during the recent period may reflect the increase of organic matter production, although minor oscillations are difficult to interpret in the records; so paleoproductivity oscillations during postglacial climatic condition in the Antarctic lakes are inher-

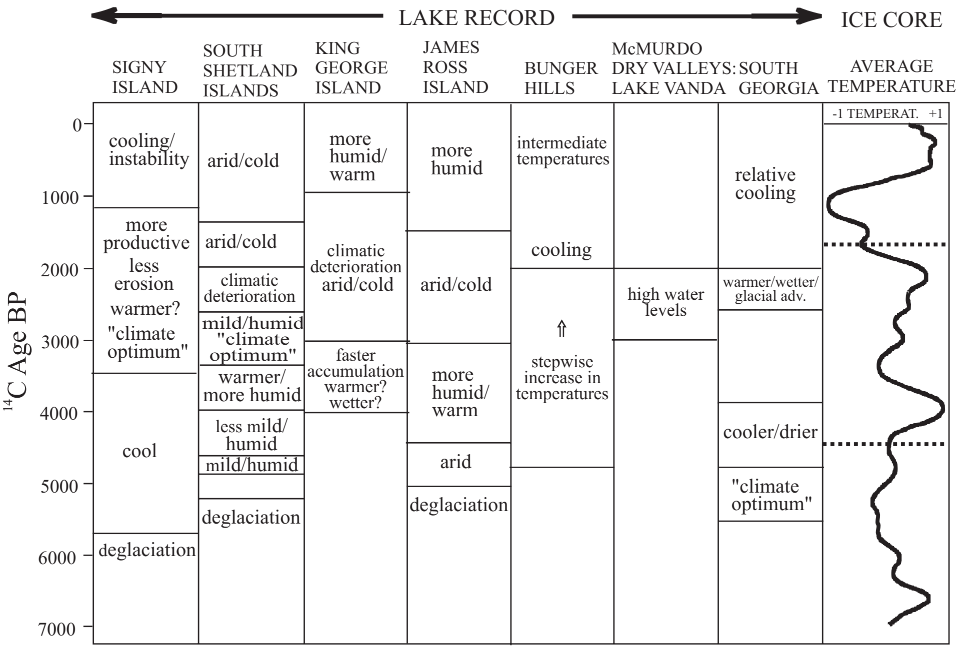


Fig. 9. Deglacial evolution stage of Antarctic lake deposit and their correlation with the air temperature variation recorded in ice core (modified from Jones *et al*. 2000).

ently more subtle than the large glacial/interglacial fluctuations recorded in Antarctic ice cores and marine sediment cores.

Conclusions

King George Island has been regarded as one of the key areas in the elucidation of the post-glacial history of the South Shetland Islands. At present, the island is surrounded by ice cliffs marginal to the low-profile ice cap of the Fildes Peninsula, the largest ice-free area on King George Island. The postglacial history of South Shetland Islands is a subject of lively debate, which ranges around two issues in respect of the timing of deglaciation. In our study, the initiation of the lakes on the King George Island is confirmed by textural contrast as well as geochemical, isotope, and paleontological evidences. It commenced *c.* 4 kaBP. The postglacial paleoproductivity variation is shown by recent increased TOC, Si_{bio} and $\delta^{13}C$ values. These suggest that there was enhanced productivity during the warm periods; a notion further substantiated by correlations with other evidences from nearby areas. However, the terrestrial signal which records the paleoproductivity change during the Holocene is much weaker than that relating to the marine indication.

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