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Article

Holocene Variations of Organic Carbon Contents in Lake Langer of King George Island, South Shetland Islands, West Antarctica

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Abstract : A sediment core drilled from Lake Langer on King George Island was analyzed for a variety of textural and geochemical properties along with ^{14}C age dates. These data were combined with published records of other cores to provide a detailed history of Holocene variation of total organic carbon (TOC) contents with respect to terrestrial paleoclimate change. The lithologic contrast of the lower diamicton and upper fine-grained sediments shows the glacier activity and subsequent lake formation. Low TOC contents fluctuated during the diamicton deposition whereas the increase of TOC began with the lake formation during the postglacial period that started about 5,000 yr B.P. More notable are the distinct TOC peaks that may imply enhanced primary productivity during the warm period. The uniform and low TOC contents may reflect the limited productivity during the evolution of the lake. However, the recent TOC readvance clearly indicates gradual warming on King George Island. However, the paleoclimatic signature in the terrestrial lake environment during the Holocene seems to be subtle and less distinct, compared to the marine environment.

Key words : organic carbon, lake sediment, paleoclimate, Antarctic

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1. Introduction

There is a great potential for the lake sediments in the maritime Antarctic to provide data for a paleoenvironmental reconstruction. Conformable Holocene sequences have been found from sites along the Antarctic Peninsula and the outcrops and lakes in the islands (Holdgate 1977; Mäusbacher *et al.* 1989; Schmidt *et al.* 1990; Björck *et al.* 1993, 1996; Yang and Harwood 1997). Due to the limited impact of human activity, lake sediments from the maritime Antarctic have been used to elucidate the effect of climate impact during the Holocene period (Birnie 1990; Fulford-Smith and Sikes 1996; Jones *et al.* 2000; Roberts *et al.* 2001). A lot of lake sediment from different islands such as Livingstone Island (Björck *et al.* 1993), James Ross Island (Ingolfsson *et al.* 1998; Björck *et al.* 1996) were investigated using the multiproxy approaches with a main focus on the freshwater diatoms (Mäusbacher *et al.* 1989; Schmidt *et al.* 1990; Yang and Harwood 1997). Integrated with glacial stratigraphic and geomorphic results, the contrasting climatic stages (arid and cold vs. humid and warm) were reconstructed to correlate with marine climate variation.

The debate on the nature of the Holocene environmental history of the South Shetland Island is still unsolved mainly due to insufficient data. One prominent argument on the main deglaciation is from John (1972) and Sugden and Clapperton (1986) who have suggested the occurrence of deglaciation before 10,000 yr B.P. In contrast, Mäusbacher *et al.* (1989) reported that the deglaciation started between 9000 and 5000 yr B.P. on King George Island. Since deglaciation, Björck *et al.* (1993) demonstrated that a climatic optimum with mild and humid conditions spans between

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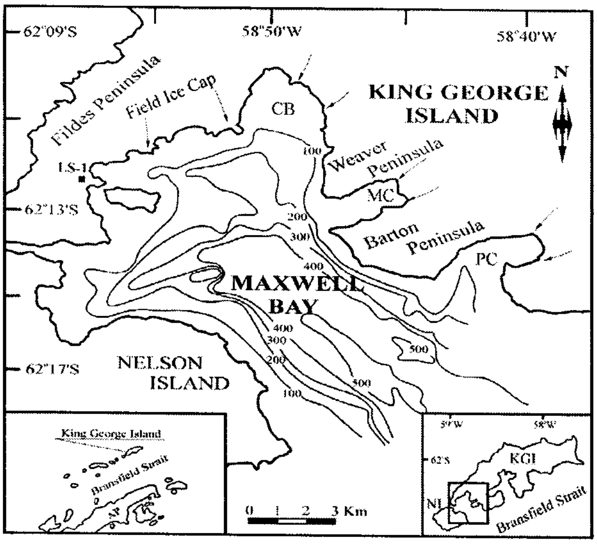

Fig. 1. Study area and location of sediment core LS-1 collected from the Lake Langer on King George Island, South Shetland Islands, west Antarctica.

3200 and 2700 yr B.P., which triggered the glacial readvance. Similarly, Schmidt *et al.* (1990) reported that the increased allochthonous input occurred between 4700 and 3200 yr B.P. on King George Island.

We have conducted a multistratigraphic analysis to a radiometrically-dated core (LS-1) obtained from Lake Langer on King George Island, South Shetland Islands of west Antarctica (Fig. 1). Various lithologic and geochemical parameters allow for the reconstruction of Holocene variation of total organic carbon (TOC) contents on King George Island.

2. Material and methods

A 7.5-m long drilling core was obtained from the Lake Langer near the Chinese Antarctic Base with logistic support from Chinese scientists (Fig. 1). All segmented core sediments were delivered to the laboratory for further analysis. The cores were cut in half and the slide for X-radiograph was obtained from one half of the core sample. Due to the small diameter of the core, the subsamples were collected from the remaining half, after measuring the magnetic susceptibility.

Magnetic susceptibility was measured on a Bartington MS-2C magnetic susceptibility sensor, scanning at 1 cm intervals with a portable point sensor. For 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.

Part of the subsamples were dried in a freezer-drier and ground by hand for geochemical analysis. Total carbon (TC) and total nitrogen (TN) were measured using a Carlo-Erba NA-1500 Elemental Analyzer. The precisions for TC and TN were ±0.4% and ±0.1%, respectively. Total inorganic carbon (TIC) was analyzed by a UIC coulorometry (CM 5130) with a precision of ±1%. Total organic carbon (TOC) was calculated from the difference between TC and TIC.

Accelerator mass spectrometry (AMS) radiocarbon (^{14}C) ages were measured at the Institute of Geological & Nuclear Sciences (New Zealand) from an acid-insoluble organic matter fraction of bulk sediments due to the lack of carbonate fossils.

3. Results

The core LS-1 is divided into two major parts, based on textural contrast in the lithology and X-radiography (Fig. 2). The upper part (about 300 cm in thickness) of the core is composed of fine-grained sediments with abundant plant remains whereas the lower part consists of mixed gravels, sands, and muds typical of diamictons. The clean sandy layer and dark mud layer are intercalated in the upper part of the core (Fig. 2). Magnetic susceptibility (MS) distinctly

Fig. 2. X-radiograph showing the overall features of sediment lithology, which is divided into two major parts. The upper part (A and B) is composed of the fine-grained sediments, whereas the lower part (C and D) consists of diamictons.

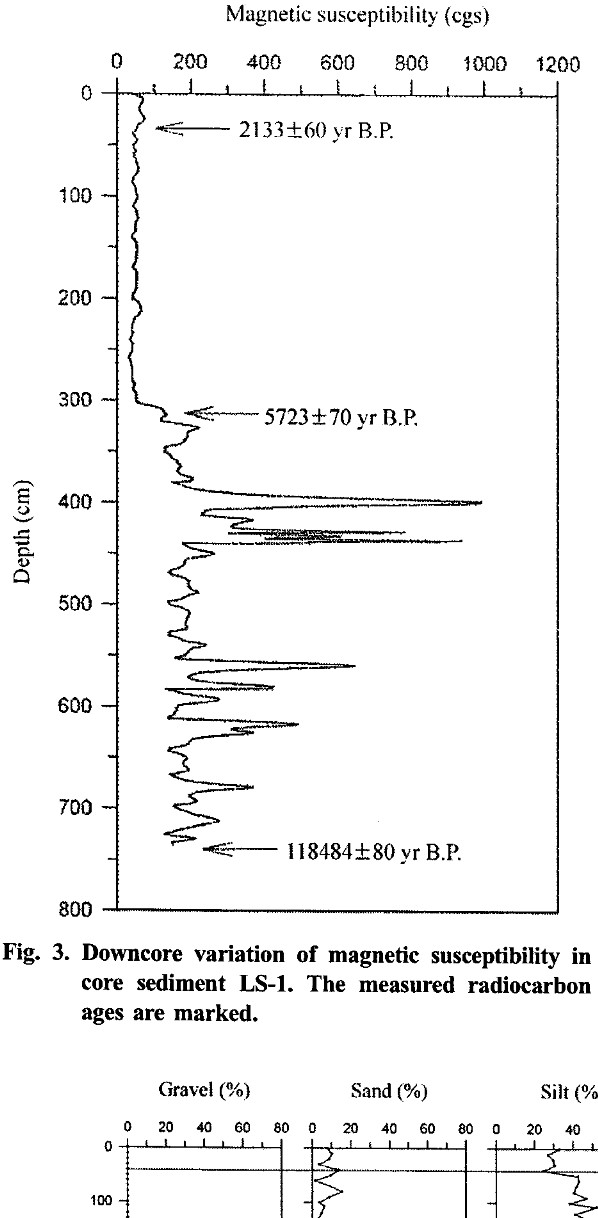

Fig. 3. Downcore variation of magnetic susceptibility in core sediment LS-1. The measured radiocarbon ages are marked.

confirms the combination of both lithologies in accordance with its magnitude; the upper part of the core shows a low signal of less than 100 cgs, whereas the lower diamicton is characterized by the large fluctuations between 200 and 1000 cgs (Fig. 3). The MS intensity is controlled by the degree of magnetic minerals within the sediments (Karlin 1990). The great quantity of gravel and sand in the lower part corresponds to the increase of MS intensity. The downcore MS variation is also checked for grain size variation (Fig. 4). The uniform mean grain size in the upper part of the core, except for the sandy layer (at 245 cm) matches the low MS intensity. Thus, the scattered presence of gravel-size particles is a main component in enhancing the MS intensity. The fluctuation of gravel contents in the lower part of the core may reflect the advance and retreat of the ground ice during the glacial period (Fig. 4).

Downcore variation of geochemical properties of core LS-1 sediments highlights the lithologic differentiation supported by mean grain size and MS (Fig. 5). The total nitrogen (TN) and total organic carbon (TOC) contents are somewhat higher in the upper part than in the lower part, whereas $CaCO_3$ contents and C/N (TOC/TN) ratios show the opposite trend. TOC contents in the upper part are mostly about 0.3%, except for the high values, which is higher than that of the reported modern surface sediments from the Andvord Bay (Domack *et al.* 1995). The parallel variation between TN and TOC reflects the common source, likely organic matter of carbon and nitrogen, but the high C/N ratio in the lower part may be due to the selective degradation of terrestrial organic nitrogen (Kemp *et al.*

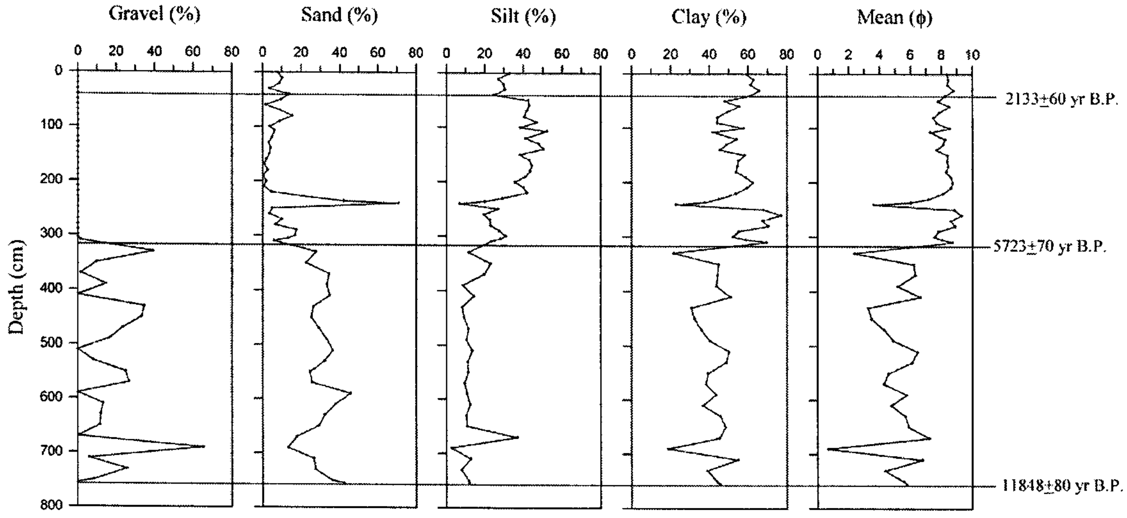

Fig. 4. Downcore variation of sedimentological properties (granulometric contents and mean grain size) in core sediment LS-1. The measured radiocarbon ages are marked.

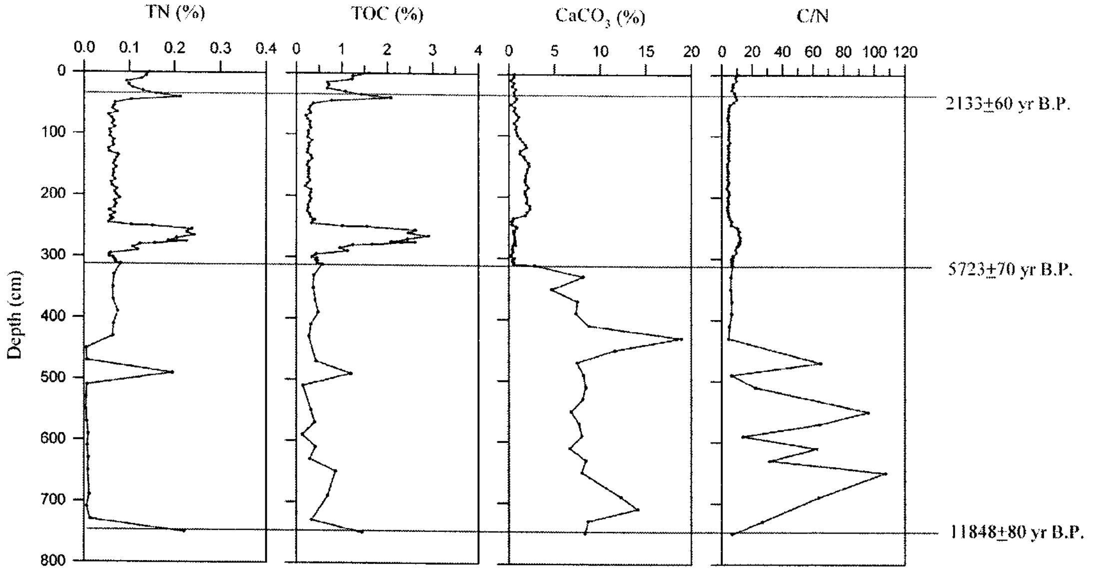

Fig. 5. Downcore variation of geochemical properties (total nitrogen, total organic carbon, and $CaCO_3$ contents and C/N ratios) in core sediment LS-1. The measured radiocarbon ages are indicated.

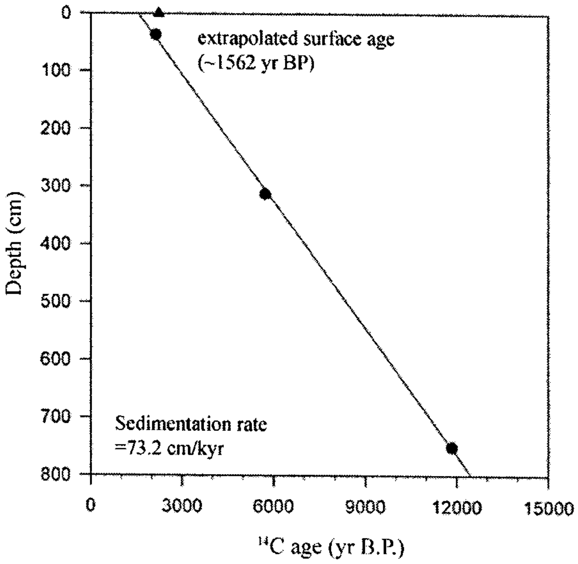

Fig. 6. Age-depth relationship showing the apparent sedimentation rate. An odd ^{14}C age determined for surface sediment was not used for the sedimentation rate calculation.

1977). The distinct peaks of TN and TOC in the upper part are very characteristic, indicating the enhanced production of organic matter, or better preservation.

Although the ^{14}C age determination is performed by sediment organic carbon, there is no reversal through the core except for surface age (Fig. 6). In general, the ocean reservoir effect for Antarctic marine carbonates is regarded as about 1200 to 1300 years (Berkman and Forman 1996; Gordon and Harkness 1992). Essentially equivalent surface ages (~1200 yr B.P.) of organic matter were also reported in the Palmer Deep of Antarctic Peninsula (Domack *et al.* 2000). Uncorrected surface age of the uppermost part of core LS-1 is 2232 yr B.P., significantly older than can be accounted for by the normal reservoir correction for the Antarctic marine environment. It is probably due to contamination by older carbons. This surface odd age was not used for calculating the sedimentation rate. The ^{14}C-age chronology demonstrates that the upper part of LS-1, fine-grained sediments, was deposited during the postglacial period of the Holocene (Fig. 5).

4. Discussion

Upward extrapolation of the linear sedimentation rate results in an assumed core-top age of about 1560 yr B.P. that lies within the range of the reservoir effect (Björck *et al.* 1991; Domack 1992; Andrews *et al.* 1999). Thus, the older ages of the Antarctic surface sediments can be explained by two major effects: (1) the large and regionally variable reservoir effect of 1200-1400 years (Andrews *et al.* 1999) and (2) possibly significant inputs of older sediments eroded, reworked and transported by glacier activity (Domack *et al.* 1989). The age/depth relationship shows that no significant variation in the sedimentation rate occurred throughout the core. The linear sedimentation rate was calculated by interpolation between the dated levels, although sedimentation rate might vary during the deposition. The apparent linear sedimentation rate is 73.2 cm/Ky. This sedimentation rate is in the middle of reported values in the terrestrial environment. The sedimentation rates in the Marguerite Bay and Gerlache Strait in the Antarctic Peninsula are about 20-50 cm/Ky (Harden *et al.* 1992), but 100-250 cm/Ky was reported in Lallemand Fiord, Andvord Bay and Granite Harbor (Leventer *et al.* 1993; Domack and McClennen 1996; Kirby *et al.* 1998; Taylor *et al.* 2001). If we subtract the extrapolated core-top age as a reservoir effect to account for the corrected age, the lithologic transition corresponds to about 4,300 yr B.P., which accords with the published age for the beginning of lake formation in the South Shetland Islands (Mäusbacher *et al.* 1989; Schmidt *et al.* 1990; Björck *et al.* 1993).

Diamictons (ground tills) in lake environments are formed by mountain glaciers in the terrestrial environment (John 1972; Clapperton and Sugden 1982; Sugden and Clapperton 1986). The thick diamicton deposit in the lower part indicates that the ground glaciers had fluctuated before the formation of the postglacial lake environment at about 5,000 yr B.P. (Fig. 4). This result supports the conclusion of Mäusbacher *et al.* (1989) that deglaciation and initiation of a limnic environment occurred between 5500 and 5000 yr B.P. on King George Island. The fine-grained sediments in the late Holocene were deposited by the supply of meltwater derived from the nearby continental region. In the shallow marine environment, the fine-grained particles were transported from the meltwater flux during the warm period (Domack and McClennen 1996; Yoon *et al.* 2000; Khim *et al.* 2001). Thus, the introduction of fine-grained sediments into the lake also indicates the initial formation

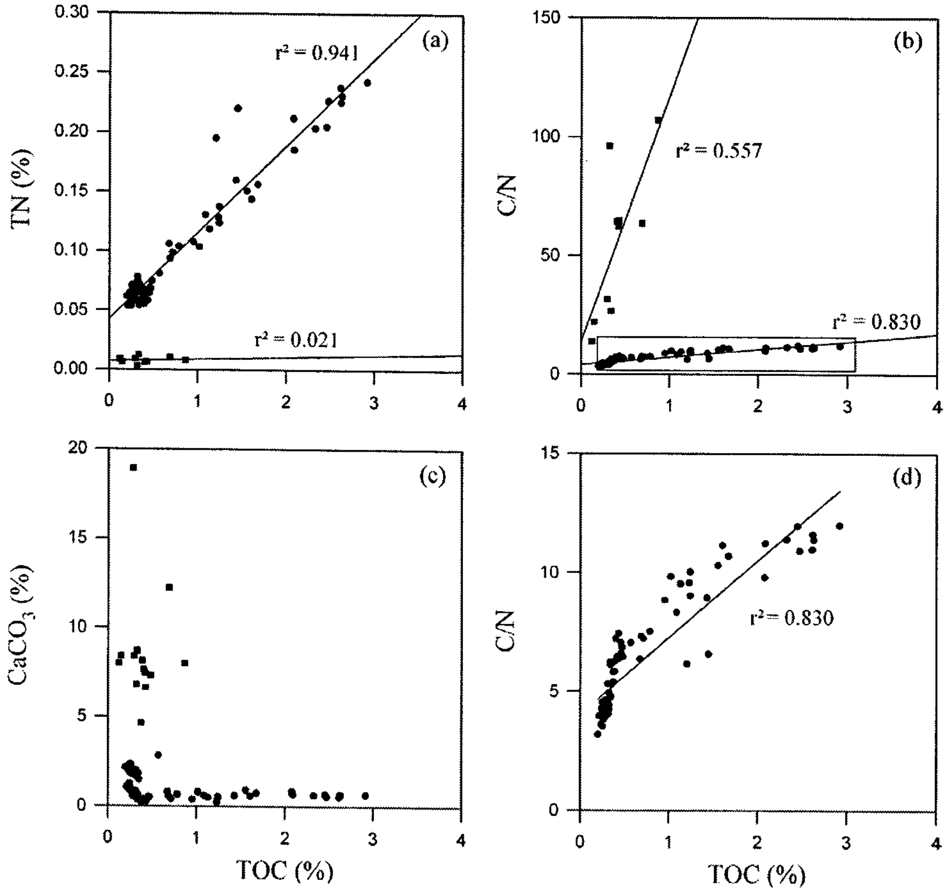

Fig. 7. (a) Correlation between total nitrogen and total organic carbon in core sediments. The relationships are divided into two parts; high TN contents with good correlation (circles) and low TN contents with poor correlation (rectangles). (b) Correlation between C/N ratios and TOC in core sediments. The relationship is also differentiated by two clusters (circles and rectangles). Details on the individual properties are referred to in the text. (c) Correlation between $CaCO_3$ and TOC contents of the sediments. (d) Enlargement of inset box in (b) showing the relationship between C/N ratios and the TOC contents of the sediments.

of a limnic environment during warm conditions.

A downcore variation in MS intensity within the core sediments may be due to diagenetic dissolution of magnetite with depth or iron-sulfur diagenesis controlled by higher organic carbon content in zones of increased productivity (Thompson and Oldfield 1986; Karlin 1990). In our core, we suggest that signal attenuation in the upper part of the core is mainly attributed to the degree of preservation of magnetic minerals, based indirectly of the granulometric contents (Fig. 4). However, the productivity cycles recognized in the marine sediment cores around the Antarctic Peninsula region result in the concurrent MS fluctuation (Shevenell *et al.* 1996; Taylor *et al.* 2001; Khim *et al.* 1999, 2002). In general, the low MS value corresponds to the high biological production period, which is characterized by the dominance of fine-grained sediments during the warm period. Further, in some cases, the fine-grained particles amplify the dilution effect in order to reduce the MS intensity. The low and uniform MS in the upper part of our core may reflect the warm period favorable for the dominant deposition of fine-grained sediments (Fig. 3).

A parallel downcore variation of TN and TOC contents implies that the carbon and nitrogen in the sediments were derived largely from the same source (Fig. 5). Such conditions can be substantiated by their correlations as shown in Figs. 7(a) and 7(b). At first glance, the organic matter seems to be differentiated by two clusters based on the correlation between TN and TOC contents; high TN contents with a good correlation (r^2=0.941) with TOC contents and low TN contents with a poor correlation (r^2=0.021) with TOC contents (Fig. 7a). The low TN contents mostly occur in diamicton (Fig. 5). During the diamicton deposition, the biological production seems to be limited and most organic matter can be delivered from the nearby terrestrial environment by erosion. In addition, the low TN contents in the lower part may be due to the selective degradation of terrestrial organic nitrogen (Kemp *et al.* 1977).

Another cluster characterized by high TN value shows a strong linear correlation (r^2=0.941) with respect to TOC, which reflects the fact that nitrogen and carbon originate from the organic matter produced in situ in the lake environment (Fig. 7a). However, according to the relationship between C/N ratio and TOC (Fig. 7d), there seems to be selective degradation of organic nitrogen in this TOC-rich sediment, resulting in the wide rang in 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 around 5 in the fine-grained sediments is attributed, not to the selective degradation of carbon, but to the incorporation of ammonia adsorbed onto the clay particles (Stevenson and Cheng 1972). Thus, the high TOC value in the upper part of core clearly indicates enhanced biological productivity. Low TOC samples show high $CaCO_3$ contents in the lower part of the core (Fig. 7c), which explains why the biological productivity is not induced by carbonate production. In general, the increase in biological productivity in lake sediments of the Antarctic region is caused by silica production mostly comprised of diatom (Birnie 1990; Fulford-Smith and Sikes 1996; Jones *et al.* 2000; Roberts *et al.* 2001). Several lake sediments on King George Island are also dominated by diatoms (Mäusbacher *et al.* 1989; Schmidt *et al.* 1990; Yang and Harwood 1997). Based on preliminary observations, high TOC contents in the upper part of the core are attributed to diatom abundance (pers. comm. with Lee, K.).

The climatic optimum seems to be a general phenomenon, although expressed in slightly different ways. Nothing very dramatic in paleoclimatic evolution is noticed on the neighboring King George Island (Mäusbacher *et al.* 1989). However, the high TOC values (250-300 cm; Fig. 5) demarcated by strong peaks undoubtedly indicate the increased primary productivity. The correspondence between the different South Shetland Islands records is also fairly good during the last 5,000 years (Mäusbacher *et al.* 1989; Schmidt *et al.* 1990; Björck *et al.* 1993). The uniform TOC value from 50 to 250 cm characterizes the more stable conditions. Readvance of TOC fluctuations in the recent period reflects an increase in the production of organic matter, although possibly minor oscillations are difficult to interpret in the records; climatic oscillations during Holocene records in the Antarctic lakes are inherently more subtle than the large glacial/interglacial fluctuations recorded in Antarctic ice cores and marine sediment cores.

5. Conclusion

King George Island has been regarded as one of the important areas in the South Shetland Islands in west Antarctica. At present, this island is surrounded by ice cliffs creeping from the low-profile ice cap of Fildes Peninsula, the largest ice-free area on King George Island. The unsolved debate on the postglacial history of the South Shetland Islands is divided into two parts, sponsoring a debate over the timing of deglaciation. In our study, the initiation of lake formation on King George Island is confirmed by textural contrast as well as geochemical properties, which started at about 5,000 yr B.P. The postglacial TOC variation shows that increased peaks indicate the enhanced productivity, substantiated by correlations with other properties. However, the terrestrial signal to record the paleoclimatic change during the Holocene period is not strong compared to the marine conditions.

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