Holocene paleolimnological changes of Lake Oyako-ike in the Soya Kaigan of East Antarctica

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Abstract

We studied Holocene paleolimnological changes as a part of studies of global change in Lake Oyako-ike in the Soya Kaigan of Lützow-Holm Bay region in East Antarctica, inferred from organic components and microscopic observation of microalgae and cyanobacteria in a sediment core (Ok4C-01, core length 135 cm), along with sedimentary facies and accelerator mass spectrometry (AMS) ¹⁴C dating. The Ok4C-01 core was composed mainly of silt and fine sand containing laminae between 135 and 65.5 cm, overlain by cyanobacterial mud between 65.5 and 0 cm. The mean sedimentation rate and crustal uplift rate were estimated to be 0.69 mm/y and 2.2 mm/y, respectively. The crustal uplift rate of Lake Oyako-ike basin is similar to those of present uplift rates but is somewhat greater than those estimated in the Lambert Glacier region, East Antarctica. The low biological production with diatoms in coastal marine environments (135–74.75 cm, ca. 2170–1300 cal BP) changes into green sulfur bacteria in stratified saline lake environments (74.75–60.95 cm, 1300–1100 cal BP), and then high biological production with cyanobacteria and green algae in freshwater environments (60.95–0 cm, 1100–220 cal BP). The ongoing retreat of glaciers and ongoing isostatic uplift during the mid-Holocene Hypsithermal (4000–2000 years ago) and thereafter are the main reasons for this isolation, whereas eustatic sea level change is believed to have played only a minor role.

Key words: AMS ¹⁴C dating, Antarctic lake, microalgae, cyanobacteria, organic components, paleolimnology, sediment core, Soya Kaigan

Introduction

Studies on paleolimnological and paleoenvironmental changes are important to estimating the possible influence of future global warming induced by human activity. Since the Last Glacial Maximum (LGM; ca. 21 ka) geological evidence from land in the Antarctic shows that there were 2 marked warm periods in the Holocene, one 11500–9000 years ago, and one in the mid-Holocene called the mid-Holocene Hypsithermal (MHH; 4000–2000 years ago; Turner et al. 2009). Lake sediment cores record global, regional, and local signals, such as climatic change, relative sea level changes, the advance and retreat of catchment glaciers, and paleoecology of biological production and biological species composition.

Since the LGM paleoenvironmental and paleolimnological changes in the Soya Kaigan of Lützow-Holm Bay region, East Antarctica has been studied mainly by

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Japanese Antarctic Research Expedition members (Yoshida and Moriwaki 1979, Miura et al. 1998a, 1998b, Matsumoto et al. 2006, 2010, Ohzono et al. 2006, Yamane et al. 2011, Takano et al. 2012). The Holocene marine limit along the Soya Kaigan is estimated to have been approximately 18 m a.s.l., based on the radiocarbon dating of in situ fossils in raised beach deposits, such as bivalve fossils (*Laternula elliptica*; Miura et al. 1998a, 1998b). Changes from marine to freshwater environments are recorded in lower altitude lakes in the Soya Kaigan due to the recession of glaciers and subsequent isostatic uplift during the MHH (Matsumoto et al. 2010, Takano et al. 2012).

Total organic carbon (TOC) and total nitrogen (TN) contents are proxies of biomass and biological production in lake sediment cores (e.g., Matsumoto et al. 2003, 2010, 2012). Chlorophyll compounds and carotenoids as well as microalgae and cyanobacteria reveal the biological composition and paleoecology (Verleyen et al. 2004a, 2004b, Hodgson et al. 2005, 2006, Matsumoto et al. 2010). Here we studied as a part of the study of global change Holocene paleolimnological changes in Lake Oyako-ike of the Soya Kaigan in East Antarctica inferred from organic components including TOC and TN contents, chlorophyll compounds, and carotenoids as well as microscopic observation of microalgae and cyanobacteria in the Ok4C-01 sediment core, along with sedimentary facies and Tandetron accelerator mass spectrometry (AMS) ^14^C dating. These studies include transition from marine, saline lakes to freshwater lake environments, and changes in biological production and biological species associated with the ongoing retreat of glaciers during the MHH and ongoing isostatic uplift of the lake basin. These are discussed in relation to Antarctic climatic and paleoenvironmental changes.

**Materials and methods**

**Study sites and samples**

Lake Oyako-ike (69°28.529S, 39°36.169E) is a freshwater lake located at Skarvsnes, the largest ice-free area (61 km^2^) along the Soya Kaigan of East Antarctica (Fig. 1). The altitude, length, width, area, maximum depth, and the distance from the sea of Lake Oyako-ike are 2.37 m (Takano et al. 2012), 430 m, 150 m, 54 000 m^2^, 6.83 m (Seto et al. 2002), and 165 m (Imura et al. 2003), respectively. The lake surface is covered with thick ice except during the austral summer. Currently, the lake water is supplied from meltwater streams of snow drift and permafrost (Imura et al. 2003). The sediment core sample of Lake Oyako-ike (Ok4C-01, water depth 6.13 m, core length 135 cm) was taken using a piston corer from the lake ice by Koji Seto on 14 January 2005 and kept frozen at −30°C at the National Institute of Polar Research.

**Analytical methods**

**Soft X-ray photography**

Sediment samples were placed in a plastic case for soft X-ray shooting (1 cm thick), taken by the use of a soft X-ray shooting apparatus (M-60: SOFTEX, Ltd, Japan) under 40 kV and 3 mA.

**AMS ^14^C dating**

AMS ^14^C dating of bulk organic carbon or algal debris was carried out by a Tandetron type-II instrument (Model 4130 AMS, HVEE) housed at Nagoya University (Watanabe et al. 2009). AMS radiocarbon data (^14^C/^12^C) were corrected to reflect the conventional age by simultaneous measurement of δ^13^C. Conventional ages were converted to calibrated years before present (cal BP) for freshwater sediment (McCormac et al. 2004) and for marine sediment (Reimer et al. 2009). A reservoir correction was applied to radiocarbon dates derived from marine samples by subtracting 1300 years, following recent conventions for the Southern Ocean (Berkman et al. 1998).

**Elemental analyses**

Elemental analyses were carried out by the methods of Matsumoto et al. (2010). Total carbon (TC) and total sulfur (TS) contents were determined at 2.3 cm intervals by a Fison NCS 2500 automatic elemental analyzer. TOC and

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**Fig. 1.** Location of Lake Oyako-ike in the Soya Kaigan of East Antarctica (revised from Imura et al. 2003).
TN contents were determined by the same analyzer, after treatment with 6 M hydrochloric acid to remove inorganic carbon. Total inorganic carbon (TIC) content was calculated by subtracting the TOC content from the TC content.

Chlorophyll compounds and carotenoids
Chlorophyll compounds and carotenoids were analyzed by a method described previously (Tani et al. 2009). Chlorophyll compounds and carotenoids were ultrasonically extracted with acetone and analyzed by a high-performance liquid chromatography (HPLC; LC-10A, Shimadzu, Japan) using photodiode array detection (SPD-M10A VP, Shimadzu, Japan). Pigments were identified by comparing absorption spectra (300–700 nm) and HPLC retention time with those of authentic standards, and by comparing with values in the literature (Harradine et al. 1996, Tani et al. 2009).

Algae and cyanobacteria
The frozen sediment core samples were melted at room temperature. A piece of sample was observed for identification using a light microscope (Olympus, BX60) with magnification up to 1000×. The relative abundance of the identified species was expressed as 5 categories; very abundant (>50%), abundant (50–30%), common (30–10%), rare (10–5%), or very rare (<5%). The samples for diatom analysis were gently digested with pure water for several minutes. Water solution of treated subsample was mounted on a coverslip, adjusting the amount so that diatom density would be suitable for the microscopic observation and taking care that the treatment did not destroy the structure of the diatom valves. Diatom identification and nomenclature were based on Kramer and Lange-Bartalot (1986, 1988, 1991a, 1991b) and Watanabe (2005).

Results and discussion

Paleoenvironmental change in the Soya Kaigan area of East Antarctica
Reconstructed data of the post-glacial climate variability along East Antarctic coastline using terrestrial and shallow marine geological records compared with data from other areas show a near-synchronous early Holocene climate optimum (11.5–9 ka BP) and the mid- to late-Holocene warm period between 4.7 and 1 ka BP, although there are some differences of regional timing (Verleyen et al. 2011). Holocene relative sea level changes in East Antarctica have been studied in the Vestfold Hills (Zwart et al. 1998), the Lambert Glacier region (Verleyen et al. 2005), and the Soya Kaigan (Matsumoto et al. 2010, Takano et al. 2012) by dating the freshwater–marine and marine–freshwater transitions recorded in lake sediment cores of isolation basins formerly connected to the sea. The contribution from global eustatic sea level is considered negligible because the global sea level fall has been estimated as 0.7 ± 0.1 m between 4000 and 2500 years BP (Goodwin 1998).

The Holocene marine limit along the Soya Kaigan is estimated to have been approximately 18 m a.s.l. based on analyses of raised beach deposits (Miura et al. 1998a, 1998b). Matsumoto et al. (2010) reported that Holocene relative sea level changes of Lake Skallen Oike in the southern part of the Soya Kaigan at an altitude of 10 m a.s.l. based on the transition from marine to freshwater environments occurred at a depth of 152.5 cm (ca. 3590 cal BP) due to the retreat of glaciers during the MHH and ongoing isostatic crustal uplift of this region. The mean isostatic crustal uplift rate of Lake Skallen Oike is calculated to be 2.8 mm/y (Matsumoto et al. 2010), although Takano et al. (2012) reported a crustal uplift rate of 3.2 mm/y in the same lake. These uplift rates are, however, consistent with present uplift rates estimated by bedrock GPS (2.3 ± 0.3 mm/y) and Very Long Baseline Interferometry (VLBI; 4.6 ± 2.2 mm/y; Kaminuma 2008). The relative crustal uplift rates of the Soya Kaigan are somewhat greater than those estimated in the Lambert Glacier region (1.8–1.9 mm/y; Verlayen et al. 2005) and in the nearby Vestfold Hills (Zwart et al. 1998).

Sedimentary sequences and the timing of the transition of coastal marine to saline lake and to freshwater lake
Core descriptions and soft X-ray photography showed that the Ok4C-01 sediment core was composed of cyanobacterial mud (surface to 61.5 cm), cyanobacterial silt (61.5–65.5 cm), silt with lamina (65.5–83.7 cm), and silt and fine sand (83.7–135 cm; Fig. 2). Glacial clay was found in the 22.2–24.5 cm depth. The radiocarbon (AMS 14C) chronology of the Ok4C-01 sediment core and the calibrated age–depth relationship of the core revealed that the surface (0–2.3 cm), 40.25, 97.75, and 132.25 cm depths were 304 ± 19, 752 ± 18, 1558 ± 39, and 2187 ± 56 cal BP, respectively (Table 1; Fig. 3). The ages of the surface (0 cm) and bottom (135 cm) of the core were linearly extrapolated to ca. 220 and 2170 cal BP, respectively. The mean sedimentation rate was linearly calculated to be 0.69 mm/y (r² = 0.99).

Matsumoto et al. (2010) determined the transition from coastal marine to saline lakes and then to the freshwater Lake Skallen Oike, mainly based on the peak of bacteriochlorophyll d and chlorobactene derived from green sulfur bacteria (Pfennig 1967, Borrego and Garcia-Gil 1994, Squier et al. 2002) at depths of 152.5 (ca. 3590 cal BP) and 135 cm (ca. 3360 cal BP), respectively.
Green sulfur bacteria require sulfide as an electron donor for photosynthesis, indicating the presence of a stratified water column with a chemocline and an anoxic (sulfidic) layer at the bottom of photic zone (Tani et al. 2009).

Chlorobactene was distributed in depths of 74.75–60.95 cm (ca. 1300–1100 cal BP) in the Ok4C-01 sediment core from Lake Oyako-ike (Fig. 4). In this period, Lake Oyako-ike became isolated from the coastal marine environment and stratified as the isolated marine water was overlain by freshwater supplied from meltwater to the lake surface. The ongoing retreat of glaciers during and after the MHH and ongoing isostatic uplift of the Soya Kaigan accounts for most of this change, as in the case of Lake Skallen Oike (Matsumoto et al. 2010).

The depths of the surface to 61.5 cm of the Ok4C-01 sediment core was composed of cyanobacterial mud. TC, TOC, and TN contents in the core increased from a depth of 60.95 cm to the surface (Fig. 4). The TOC/TS weight ratio near the bottom (132.25 cm) of the core was around 2, maintained near constant to a depth of 63.25, and increased dramatically from a depth of 60.95 cm to the surface to a value of approximately 4 (Fig. 4). This strongly suggests a change from marine to freshwater sediments in the core because the TOC/TS ratios of marine sediments are generally much lower than those of freshwater sediments (Berner and Raiswell 1984, Sampei et al. 1997). The transition periods from coastal marine to saline lake and to freshwater lake of Lake Oyako-ike basin are, therefore, probably 74.75 cm (ca. 1300 cal BP) and 60.95 cm (1100 cal BP), respectively. Crustal uplift rate of the catchment can be linearly estimated to be 2.2 mm/y based on the transition period from coastal marine to saline water environment. This period is similar to the result of 1060 ± 90 cal BP reported by Takano et al. (2012). The crustal uplift rate of Lake Oyako-ike basin is similar to those of present uplift rates, as discussed earlier.

**Coastal marine environment (135–74.75 cm, ca. 2170–1300 cal BP)**

The Ok4C-01 sediment core was composed of silt and fine sand in depths 135–83.7 cm and composed of silt with lamina in depths of 83.7–65.5 cm. The soft X-ray photographs (Fig. 2) showed dark and consistent images with low TOC contents. The high TIC peak was found in depths of 130–100 cm, which is a contribution of sea shelf and foraminifera in the sediment.

Small amounts of chlorophyll $a$, pheophytin $a$, pyropheophytin $a$, cis-diaxanthin, pheophytin $b$, pyropheophytin $b$, and cis-alloxanthin were detected in depths of 135–74.75 cm (Fig. 5). Chlorophyll $a$, pheophytin $a$, and
pyrophephytin \( a \) are commonly distributed in photosynthetic organisms (Tani et al. 2009, Matsumoto et al. 2010). *Cis*-diatoxanthin is distributed in green algae, diatoms, and cyanobacteria, but pheophytin \( b \) and pyrophephytin \( b \) are distributed in green algae, brown algae, and vascular plants. No brown algae and vascular plants are, however, distributed in the studied area. *Cis*-alloxanthin is a typical carotenoid of Cryptophyta (Jeffrey et al. 1997, Tani et al. 2009, Matsumoto et al. 2010). Marine diatoms, *Paralia sulcata* and *Tryblionella litoralis*, were distributed in depths of 102.35 and 132.25 cm, in addition to the abundance of *Staurosira* sp. and small number of *Hantzschia* sp., which may be saline–marine diatoms (Table 3). This finding suggests coastal marine water was diluted with glacial meltwater in the basin. *Cis*-diatoxanthin may be derived from those diatoms.

**Stratified saline lake environment** (74.75–60.95 cm, ca. 1300–1100 cal BP)

Ubiquitous photosynthetic pigments of chlorophyll \( a \), pheophytin \( a \), and pyrophephytin \( a \) were found in these

![Fig. 4](image-url)  
**Fig. 4.** Total carbon (TC), total organic carbon (TOC), total nitrogen (TN), total inorganic carbon (TIC), and total sulfur (TS) contents, and TOC/TC, TOC/TN, and TS/TOC weight ratios in the Ok4C-1 sediment core from Lake Oyako-ike.

![Fig. 5](image-url)  
Table 1. Conventional and calibrated age of the Ok4C-1 sediment core from Lake Oyako-ike.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (cm)</th>
<th>$\delta^{13}$C (‰) vs. PDB</th>
<th>$^{14}$C age$^a$ yrBP ± 1 sigma</th>
<th>Dataset</th>
<th>Calibrated age cal BP ± 1 sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ok001</td>
<td>1.15</td>
<td>$-16.3 \pm 0.3$</td>
<td>294 ± 23</td>
<td>SHCal04</td>
<td>304 ± 19$^b$</td>
</tr>
<tr>
<td>Ok018</td>
<td>40.25</td>
<td>$-18.0 \pm 0.2$</td>
<td>895 ± 21</td>
<td>SHCal04</td>
<td>752 ± 18$^b$</td>
</tr>
<tr>
<td>Ok043</td>
<td>97.75</td>
<td>$-15.3 \pm 0.3$</td>
<td>2899 ± 24</td>
<td>Marine09</td>
<td>1558 ± 39$^c$</td>
</tr>
<tr>
<td>Ok058</td>
<td>132.25</td>
<td>$-16.2 \pm 0.2$</td>
<td>3411 ± 23</td>
<td>Marine09</td>
<td>2187 ± 56$^c$</td>
</tr>
</tbody>
</table>

$^a$Conventional age.

$^b$Data were calibrated with Southern Hemisphere samples from McCormac et al. (2004).

$^c$Data were calibrated with marine reservoir effects (Reimer et al. 2009). A reservoir correction was applied to radiocarbon dates derived from marine samples by subtracting 1300 years following recent conventions for the Southern Ocean (Berkman et al. 1998).

Table 2. TOC, TN, TS contents and their ratios (average ± standard deviation) for Ok4C-1 sediment core from Lake O-ike.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Freshwater lake environment</th>
<th>Saline lake environment</th>
<th>Coastal marine environment</th>
<th>A/B</th>
<th>A/C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface–60.95 cm (A)</td>
<td>63.25–74.75 cm (B)</td>
<td>77.05–132.25 cm (C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of samples</td>
<td>27</td>
<td>6</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOC (%)</td>
<td>$6.84 \pm 3.33$</td>
<td>$1.57 \pm 0.47$</td>
<td>$0.889 \pm 0.336$</td>
<td>4.36</td>
<td>7.69</td>
</tr>
<tr>
<td>Range ± SD (%)</td>
<td>$1.36–12.9$</td>
<td>$1.11–2.43$</td>
<td>$0.356–1.62$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TN (%)</td>
<td>$0.951 \pm 0.382$</td>
<td>$0.241 \pm 0.030$</td>
<td>$0.232 \pm 0.065$</td>
<td>3.95</td>
<td>4.10</td>
</tr>
<tr>
<td>Range ± SD (%)</td>
<td>$0.261–1.57$</td>
<td>$0.197–0.281$</td>
<td>$0.112–0.369$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS (%)</td>
<td>$1.94 \pm 0.62$</td>
<td>$1.54 \pm 0.16$</td>
<td>$0.750 \pm 0.373$</td>
<td>1.26</td>
<td>2.59</td>
</tr>
<tr>
<td>Range ± SD (%)</td>
<td>$1.09–2.71$</td>
<td>$1.39–1.81$</td>
<td>$0.242–1.78$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOC/TN</td>
<td>$6.81 \pm 0.92$</td>
<td>$7.54 \pm 1.12$</td>
<td>$5.66 \pm 0.78$</td>
<td>0.90</td>
<td>1.20</td>
</tr>
<tr>
<td>TOC/TS</td>
<td>$3.88 \pm 2.67$</td>
<td>$1.03 \pm 0.37$</td>
<td>$1.32 \pm 0.50$</td>
<td>3.77</td>
<td>2.94</td>
</tr>
<tr>
<td>Range ± SD</td>
<td>$0.995–11.8$</td>
<td>$0.72–1.76$</td>
<td>$0.64–2.92$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Algae and cyanobacteria found in the Ok4C-1 sediment core from Lake Oyako-ike.

<table>
<thead>
<tr>
<th>Species</th>
<th>Depth (cm)</th>
<th>1.15</th>
<th>28.75</th>
<th>56.35</th>
<th>60.95</th>
<th>70.15</th>
<th>102.35</th>
<th>132.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyanophyceae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cf. Leptolyngbya spp.</td>
<td>cc</td>
<td>cc</td>
<td>cc</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>Bacillariophyceae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amphora oligotraphenta</td>
<td>cc</td>
<td>cc</td>
<td>cc</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Hantzschia sp.</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>r</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Paralia sulcata</td>
<td>rr</td>
<td>—</td>
<td>rr</td>
<td>+</td>
<td>rr</td>
<td>rr</td>
<td>cc</td>
<td></td>
</tr>
<tr>
<td>Navicula cryptocephala</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>c</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Staurosira sp.</td>
<td>—</td>
<td>—</td>
<td>r</td>
<td>+</td>
<td>rr</td>
<td>c</td>
<td>rr</td>
<td></td>
</tr>
<tr>
<td>Tryblionella littoralis</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>r</td>
<td>—</td>
<td>r</td>
<td>rr</td>
</tr>
<tr>
<td>Chlorophyceae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oedogonium sp.</td>
<td>r</td>
<td>—</td>
<td>—</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>Cosmarium clepsydra</td>
<td>c</td>
<td>cc</td>
<td>c</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>Cosmarium subcrenatum</td>
<td>—</td>
<td>+</td>
<td>cc</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
</tbody>
</table>

Habitat

Freshwater Freshwater Freshwater Freshwater Saline Saline/Marine Marine

cc = >50%; c = 50–30%; + = 30–10%; r = 10–5%; rr = <5%; ND = not determined.
depths (Fig. 5). Cis-diatoxanthin, pheophytin b, pyropheophytin b, and cis-alloxanthin were also distributed in these depths. The occurrence of chlorobactene can be an indicator for the presence of green sulfur bacteria, which indicates the presence of a stratified water column with a chemocline and an anoxic (sulfidic) layer at the bottom of the photic zone. The Lake Oyako-ike basin became isolated from the sea and stratified as the isolated marine water was overlain by freshwater supplied from meltwater to the lake surface.

The presence of cis-alloxanthin originates from the Cryptophyta, which are known to tolerate moderate salinity and stratified water conditions as in the case of Lake Skallen Oike (Matsumoto et al. 2010). Stratified water conditions with chemocline support both the presence of photosynthetic organisms, such as diatom and cyanobacteria in the freshwater column and green sulfur bacteria in the anoxic column of the bottom of the photic zone. The presence of cyanobacteria in this layer was evidenced by cyanobacterial silt in the core. Abundance of Navicula cryptocephara at a depth of 70.15 cm probably reflects a saline habitat (Table 2).

**Freshwater lake environment (60.95–0 cm, ca. 1100–220 cal BP)**

The Ok4C-01 sediment core was composed of cyanobacterial mud (61.5 cm–surface). Glacial clay was found in 24.5–22.2 cm depth. The X-ray photograph was transparent with lamina in the depths of surface to approximately 61 cm, except for a dark layer approximately 25–22 cm depth (Fig. 2). The TOC contents ranging from 1.36 to 12.9% with an average of 6.84 ± 3.33% in depths 60.95 cm to the surface were 7.69 times higher than those of coastal marine environment and 4.36 times higher than those of saline water environment, respectively (Table 3; Fig. 4). Freshwater lake environments are characterized by high biological production, as in the case of Lake Skallen Oike (Matsumoto et al. 2010). Stratified water column with a chemocline and an anoxic (sulfidic) layer at the bottom of the photic zone. The presence of cyanobacteria in this layer was evidenced by cyanobacterial silt in the core. Abundance of Navicula cryptocephara at a depth of 70.15 cm probably reflects a saline habitat (Table 2).

Ubiquitous photosynthetic pigments (chlorophyll a, pheophytin a, and pyropheophytin a) and various pigments of cis-diatoxanthin, zeaxanthin, pheophytin b, pyropheophytin b, lutein, and cis-alloxanthin were found in the freshwater lake environments. These pigments are derived from Leptolyngbya spp. of the Cyanophyceae; Amphora oligotraphenta of the Bacillariophyceae; and Oedogonium sp., Cosmarium clepsydra, and Cosmarium subcrenatum of the Chlorophyceae in freshwater lake conditions (Table 3). Of special interest is the preservation of morphological features of Leptolyngbya spp. and Cosmarium clepsydra at a depth of 56.35 cm (ca.1040 cal BP; Table 3).

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