Holocene paleolimnological changes in Rundvågshetta lakes of the Soya Coast region and their paleoenvironmental significance with glacio-isostatic uplift in East Antarctica

Genki INOUE (genki@otsuma.ac.jp)
Otsuma Joshi Daigaku - Chiyoda Campus: Otsuma Joshi Daigaku

Eisuke Honda
Japan Post Kabushiki Kaisha

Keisuke Ito
China University of Geosciences Beijing

Ijin Kang
Saram International Co. Ltd.

Koji Seto
Shimane Daigaku

Yukinori Tani
Shizuoka Kenritsu Daigaku

Takahiro Watanaabe
Japan Atomic Energy Agency: Nihon Genshiryoku Kenkyu Kaihatsu Kiko

Kaoru Kashima
Kyushu Daigaku

Shuji Ohtani
Shimane Daigaku

Toshiro Yamanaka
Tokyo Kaiyo Daigaku

Toshio Nakamura
Nagoya Daigaku

Yoshinori Takano
JAMSTEC: Kaiyo Kenkyu Kaihatsu Kiko

Satoshi Imura
National Institute of Polar Research Division for Research and Education: Kokuritsu Kyokuchi Kenkyujo Kenkyu Kyoikukei

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Research Article

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Abstract

We studied Holocene paleolimnological changes inferred from multi-proxy data set of CNS elements, biomarkers and microscopic observation of microalgae and cyanobacteria in sediment cores from Rundvågshetta lakes (Maruwanminami-ike and Maruwan o-ike) in the Soya Coast region of East Antarctica, along with sedimentary facies and AMS ^{14}C dating. They are discussed with paleoenvironmental changes, transition ages and glacio-isostatic uplift rates in the Soya Coast region and East Antarctica. Ages of the Maruwanminami-ike core (MwS4C-01, length 147 cm) and Maruwan-oike (Mw4C-01, length 226 cm) ranged from 1,230-5,010 cal BP) and 2,240-5,700 cal BP, respectively. Reservoir effects of the Rundvågshetta lakes were very high which may be due to the influence of dead carbon in glacially eroded marine sediments and base rocks. Average sedimentation rates of Lakes Maruwanminami-ike and Maruwan-oike were 0.389 and 0.649 mm/yr, respectively. Crustal uplift rates of Lakes Maruwanminami-ike and Maruwan-oike determined by sedimentary facies, green sulfur bacterial biomarkers and diatoms were estimated to be 8.24 and 8.25 mm/yr, respectively.

Coastal marine environment: Maruwanminami-ike (147-72.5 cm, 5,010-2,590 cal BP) and Maruwan-oike (226-47.2 cm, 5,700-3,190 cal BP) were characterized by low biological production with the predominance of diatoms. Transition period of stratified brackish lake environment: Maruwanminami-ike (72.5-65.6 cm, 2,590-2,500 cal BP) and Maruwan-oike (47.2-28.8 cm, 3,190-2,890 cal BP) were characterized by stratified conditions with marine water overlain by freshwater, and a chemocline developed together with an anoxic layer in the bottom of photic zone. Freshwater lake environment of Maruwanminami-ike (65.6-0 cm, 2,500-1,230 cal BP) was characterized by high biological production by cyanobacteria (e.g. *Leptolyngbya* spp.) and green algae (e.g. *Comarium* clepsydra) with some contribution of diatoms, while that of Maruwan-oike (28.8-0 cm, 2,890-2,240 cal BP) was very low biological production. The marine to terrestrial transition ages of raised beaches and isolated basins in the Saya Coast region ranged from 970 to 9,290 yr BP with an average of 3,660±1,520 yr BP (standard deviation) suggesting that major warm periods in the region are the middle Holocene. Glacio-isostatic uplift rates of raised basins and isolated basins in the Soya Coast region ranged from 0.19 to 4.40 mm/yr with an average of 2.0 ± 0.92 mm/yr which is similar to East Antarctica. Glacio-isostatic uplift rates of raised beaches are correlated with altitudes with a correlation coefficient of $r^2 = 0.724$. Increasing crustal uplift rates with altitudes reflect continuous crustal uplifts in the Soya Coast region.

1 Introduction

Studies on paleolimnological and paleoenvironmental changes are important to estimate the possible influence of future global warming induced by human activity. Since the Last Glacial Maximum (LGM, ca.20 ka; e.g. Ingolfsson et al. 1998; Anderson et al. 2002) geological evidence from land in the Antarctic shows that there were two marked warm periods in the Holocene, one in the 11,500-9,000 years ago, and one in the middle Holocene called the middle Holocene Hypsithermal (MHH, 4,000-2,000 years ago (Turner et al. 2009, 2014), although the MHH varies considerably in the Antarctic areas (Bentley and Hodgson 2009; Verleyen et al. 2011). These warm periods are likely to have raised temperatures by no more than around 0.5-1°C (Turner et al. 2014). Paleoenvironmental studies on the Soya Coast region in the Holocene have been carried out by retreat history of ice sheet, raised beach sediments, and isolation basins of marine environments.

Yamane et al. (2011) reported the exposure ages (^{10}Be and ^{26}Al chronology) constraining the timing of the last deglaciation from the Soya Coast region, East Antarctica and suggested that the final retreat of the ice sheet in the region occurred rapidly in the early Holocene and the reduction of the ice thickness in the region was at least 350 m. Kawamata et al. (2020) presented a new detailed ice-sheet history for the southern Soya Coast region, Lützow-Holm Bay, based on geomorphological observations and surface exposure ages (^{10}Be and ^{26}Al chronology).

Raised beach sediments up to ca. 20 m above mean sea level (hereafter, asl) are widely distributed in the Soya Coast region, together with ^{14}C ages of marine fossils (shells, polychaete tubes, and foraminifera) in these sediments have been studied mainly by many JARE members (e.g. Yoshida, 1970, 1983; Omoto et al, 1974; Omoto, 1977,1978; Hayashi and Yoshida, 1994; Igarashi et al. 1995a,b; Maemoku et al., 1997; Hirakawa and Sawagaki, 1998; Miura et al., 1998a, b, 2002). Especially, Miura et al. (1998a, b, 2002) studied extensively the stratigraphy of raised beaches with Tandetron accelerator mass spectrometry (AMS) ^{14}C ages of marine fossils of indigenous *Laternula elliptica* (*L. elliptica*) in the sediment layers of excavated trenches with maximum length of 160 m in the Soya Coast region (Ongul Islands, Langhovde, Skarvsnes, Fig. 1) and discussed the peripheral fluctuation and AMS ^{14}C age and the East Antarctic Ice Sheet (EAIS) and sea-level change since the last glaciation. They classified into two groups formed in Late Pleistocene (30,000-46,000 yBP, probably in the last interstadial), and in the middle Holocene (3,000-7,200 yBP) in East Ongul Island, Langhovde and Skarvsnes reflecting marine transgression.

Lake sediment cores record global, regional and local signals, such as climatic change, changes in relative sea level (RSL), the advance and retreat of catchment glaciers, and paleoecology of biological production and biological species composition. Changes from marine to brackish and to freshwater environments are recorded in lake sediments in the Soya Coast region due to the retreat of glaciers and subsequent isostatic uplift during the middle and late Holocene (Seto et al. 2002; Matsumoto et al. 2010, 2014; Takano et al. 2012, 2015; Verleyen et al. 2017). Based on the $^{10}Be/^{9}Be$ ratios obtained from the sediment of Lake Maruwan-oike, Sproson et al. (2021) reported a substantial increase of sub-glacial meltwater flux (< 730%) between 4.1 and 3.6 ka BP at Rundvågshetta.

Here we studied Holocene paleolimnological changes in Rundvågshetta lakes (Maruwanminami-ike and Maruwano-ike) of the Soya Coast region in East Antarctica inferred from multi-proxy data set of total carbon (TC), total organic carbon (TOC), total inorganic carbon (TIC), total nitrogen (TN), total sulfur (TS), hydrocarbons, fatty acids, sterols, chlorophyll compounds, carotenoids and/or stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) as well as microscopic observation of microalgae including diatom and cyanobacteria in Rundvågshetta lake sediment cores (MwS4C-01 and Mw4C-01), along with sedimentary facies and AMS ^{14}C dating. These studies include transition from coastal marine, brackish lake and to freshwater lake environments, and changes in biological production and biological species associated with the ongoing retreat of glaciers during the Holocene and ongoing isostatic uplift of the lake basin. They are discussed with paleoenvironmental changes, transition ages and glacio-isostatic uplift rates in the Soya Coast region and East Antarctica.

2 Methods/experimental

2.1 Study sites and samples

Imura and co-workers reported an important archive that the compilation of fundamental data on lake locations, limnological properties, electric conductivity, and description of vegetation i.e., aquatic moss (Imura et al. 2003). Rundvågshetta (69°54.5' S, 39°02'E) is a rock headland at the southwest margin of the Rundvåg Glacier (Sawagaki and Hirakawa 1997; Miura et al. 1998b; Takano et al. 2015). Lake Maruwanminami-ike (69°54’37”S, 39°02’17”E) and Lake Maruwan-oike (69°54’26”S, 39°02’41”E) are located at Rundvågshetta in the Soya Coast of East Antarctica (Fig. 1). These lakes are adjacent each other across a lateral moraine. The altitude, distance from the sea, length, width, area and maximum depth of Lake Maruwanminami-ike are 11.2 m, 200 m, 550 m, 300 m, 187,500 m^2 and 14.0 m, respectively (Fig. 2). The altitude, distance from the sea, length, width, area and maximum depth of Lake Maruwan-oike are 8.0 m, 250 m, 750 m, 350 m, 252,000 m^2 and 37 m, respectively (Fig. 2, Imura et al. 2003). The altitude of Lake Maruwanminami-ike is 3.2 m higher than that of Lake Maruwan-oike (Okuda 2005, pers. com.). The lake surfaces are covered with thick ice except during the austral summer. Nowadays the lake waters are mainly supplied from Rundvåg Glacier connected to the north side of the lakes (Fig. 1).

The sediment core of Lake Maruwanminami-ike (MwS4C-01, water depth 13.39 m, core length 147 cm) was taken using a piston corer by KS and SI on Dec. 23, 2004. The sediment core of Lake Maruwan-oike (Mw4C-01, water depth 15.07 m, core length 226 cm) was taken on Dec. 22, 2004 (Fig. 2). These sediment core samples were kept frozen at -30°C at National Institute of Polar Research and Otsuma Women’s University.

2.2 Analytical methods

2.2.1 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 (Matsumoto et al. 2014).

2.2.2 AMS ^{14}C dating

AMS ^{14}C dating of bulk organic carbon was carried out by Tandetron type-II instrument housed at Nagoya University (Watanabe et al. 2009) and Paleo Labo Co. Ltd. (Japan). AMS radiocarbon data ($^{14}C/^{12}C$) were corrected to reflect the conventional age by simultaneous measurement of $\delta^{13}C$. Conventional ages were calibrated for lacustrine sediment in Southern Hemisphere using SHCal20 (Hogg et al. 2020) and for marine sediment using Marine20 (Heaton et al. 2020). A reservoir correction was applied to radiocarbon dates derived from marine samples by subtracting 1,300 years following recent conventions for the Southern Ocean (Berkman et al. 1998).

2.2.3 Elemental analyses

Elemental analyses were carried out by the methods of Matsumoto et al. (2010). TC and TS contents were determined at 2.3 cm intervals by a Fisons NCS 2500 automatic elemental analyzer (Italy). TOC and TN contents were determined by the same analyzer, after treatment with hydrochloric acid to remove inorganic carbon. TIC content was calculated by subtracting the TOC content from the TC content.

2.2.4 Stable isotope ratios of carbon and nitrogen ($\delta^{13}C$, $\delta^{15}N$)

Stable isotope ratios of sediment samples were determined by the method of Yamanaka et al. (2010). Briefly, for TOC and TN content measurements of the sediment samples were lyophilized. A 1M HCl solution was added to remove carbonate before being dried in vacuo using NaOH pellets as a desiccant. TOC and TN contents in the sediment samples and all carbon and nitrogen isotopic compositions of TOC and TN were measured at 2.3 cm intervals using elemental analyzer/isotope ratio mass spectrometry (EA/IRMS, IsoPrime EA, GV Isogas Instruments, UK). All the isotopic values are expressed using δ notation in permil deviation (‰) from international reference materials (VPDB: Vienna Pee Dee Belemnite for $\delta^{13}C$ and atmospheric N_2 for $\delta^{15}N$). Analytical errors associated with the overall process of these determinations were less than 5% for the quantitative analyses and less than ±0.2, and ±0.3 for $\delta^{13}C$ and $\delta^{15}N$ isotopic compositions, respectively.

2.2.5 Chlorophyll compounds and carotenoids

Chlorophyll compounds and carotenoids in selected 33 sediment samples were analyzed by the method described previously (Tani et al. 2009; Matsumoto et al. 2010). The samples were ultrasonically extracted with acetone, and analyzed by a high-performance liquid chromatograph (HPLC, LC-10A, Shimadzu, Japan) using photodiode array detection (SPD-M10AVP, Shimadzu, Japan). The identification of these pigments was carried out by the comparison of absorption spectra (300-700 nm) and HPLC retention time with those of authentic standards and with comparison of literatures (Harradine et al. 1996; Tani et al. 2009).

2.2.6 Hydrocarbons, fatty acids and sterols

These biomarkers in selected 16 sediment samples were analyzed by the methods described elsewhere (Matsumoto et al. 1979, 1982, 2003, 2010). Briefly, biomarkers were extracted with ethyl acetate after saponification with 0.5M potassium hydroxide methanol (80°C, 2 h). The extracts were chromatographed through a silica gel column chromatography (length 160 mm x 6 mm i.d. 5% water). Hydrocarbons and polar fraction (fatty acids and sterols) were eluted with hexane and ethyl acetate, respectively. Fatty acids were methylated with diazomethane. Sterols were trimethylsilylated with TMS-BA (N,O-bistrimethylsilylacetmide in acetonitrile). Hydrocarbons, fatty acid methyl esters and trimethylsilyl derivatives of sterols were analyzed by a gas chromatograph-mass spectrometer (GC-MS, JMS Q1000, JEOL, Japan) equipped with a fused silica capillary column (J&W DB5 ms, 30 m, 0.25 mm i.d., film thickness 0.1 μm (Matsumoto et al. 2010).

2.2.7 Algae and cyanobacteria as primary producers

The primary producers including eukaryotes and prokaryotes in the glacial lakes are important indicators for describing sedimentary facies. The morphological features of the algae and cyanobacteria are mostly decomposed and identification of their species is impossible except for diatoms and desmids in the sediment core, and thus algae (except for diatoms) and cyanobacteria were studied less than 60 cm in core depth.

The frozen sediment core samples were melted at room temperature. A piece of sample was observed for identification of cyanobacteria and algae other than diatoms using the light microscope (Olympus, BX60, Japan) with magnification up to x1000. 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 its amount so that diatom density would be suitable for the microscope observation. We took care the treatment of diatom valves not to be destroyed their structure. Diatom identification and nomenclature were based on Krammer and Lange-Bartalot (1986, 1988, 1991a, b) and Watanabe (2005). The relative abundance of the identified species was expressed as five categories; very abundant (>50%), abundant (50-30%), common (30-10%), rare (10-5%) or very rare (<5%).

3 Results

3.1 Lake Maruwanminami-ike (MwS4C-01) sediment core

3.1.1 Lithology and geochronology

Lake Maruwanminami-ike (MwS4C-01) sediment core was composed of diatomite with lamination (147-66 cm) sandwiched by clay with lamination (98-92 cm, 70-68 cm) overlain clayey diatomite (66-64 cm) and organic mud with lamination (64-0 cm) sandwiched by clay with lamination (57-53, 31-29, 17-16, 7-0 cm) and by silt with lamination (53-51 cm, Fig. 3). Based on the previous report (Takano et al. 2015), the principal component analysis (e.g., Jolliffe and Cadima, 2016) and the correlation matrix tables for major elements in two lake sediments at Rundvagshetta (e.g., Al_2O_3, SiO_2, K_2O, CaO, TiO_2, MnO, Fe_2O_3, TC, TN, and TS) are shown in Appendices (a)-(d) to compare sedimentary facies.

The conventional and calibrated ages of TOC in the Maruwanminami-ike sediment core is shown in Table 1. Age-depth relationship showed that sedimentation rates were slightly increased with depth (Fig. 3). The calibrated age-depth relationship of the MwS4C-01 sediment core revealed that of 5.8, 35.7, 67.9, 111.6

and 143.8 cm depths were 1,355 ± 45 (2σ), 1,765 ± 65, 2,495 ± 165, 3,310 ± 140 and 4,740 ± 170 cal BP, respectively (Table 1, Fig. 3). The age of the core surface (0 cm) and bottom (147 cm) were linearly extrapolated to 1,230 and 5,010 cal BP, respectively.

3.1.2 Elemental data (TC, TOC, TN, TIC and TS)

TC, TOC, TN, TIC and TS contents near the bottom (143.8 cm) of the MwS4C-01 sediment core were approximately 2.9%, 2.6%, 0.47%, 0.28% and 1.4%, respectively, and were near constant for a depth of 70.2 cm, have a peak in depths of 70.2-61.0 cm, have low values in depths of 61.0-51.8 cm, increased dramatically and kept higher values between depths of 47-10.4 cm except for a depth of 31.0 cm, and decreased again to the surface (Fig. 4, cf. Additional file Table S1). TOC/TC values of depths between 143.8 cm-surface were mainly 60-100%, but low values (~0) were found at depths of 134.6, 111.6, 72.5 and 54.1 cm. Changes in TOC/TN and TOC/TS ratios between depths of 143.8-70.2 cm were relatively small ranging from 4 to 6 and 0.4 to 1.5 weight ratios, respectively, but higher values were found in depths of 67.9-61.0 and 51.8-8.1 cm except for a few cases (Fig. 4).

3.1.3 Hydrocarbons, fatty acids and sterols

Selected hydrocarbons, fatty acids and sterols are shown in Fig. 5 where the compositions of *n*-C_{17} alkane and diploptene were percentages of total hydrocarbons. Normal-C_{17} alkane and diploptene contents in depths of 143.8 to 56.4 cm were very low, but three peaks were found in depths of 49.5-3.5 cm with maximizing peak at a depth of 19.6 cm. Normal short-chain alkanoic acid (C_{12}-C_{19}) contents in depths of 143.8-72.5 cm were near constant of approximately 70%, decreased to 40-60% in depths of 63.3-3.5 cm, whereas long-chain *n*-alkanoic acids (C_{20}-C_{36}) were very low less than 10% in depths of 143.8-72.5 cm, but increased to 38.9% at a depth of 31.1 cm and then decreased to 10-20% in depths of 19.6-3.5 cm. Branched acids (*iso*- and *anteiso*-C_{12}-C_{18}) were low (5-15%) in depths of 143.8-49.5 cm, but higher values greater than 20% were found in depths of 40.3-8.1 cm except for a depth of 31.1 cm. Changes in C_{27} sterol (cholest-5-en-3β-ol, 5α-cholestan-3β-ol) % were generally small throughout the depth (10-40%). C_{28} sterol (24-methylcholetsa-5,22-dien-3β-ol, 24-methylcholest-5-en-3β-ol, 24-methyl-5α-choletan-3β-ol) were very high (60-80%) in depths of 143.8-70.2 cm, decreased largely to less than 20% in depths of 63.3-3.5 cm, whereas C_{29} sterol (24-ethylcholeta-5,22-dien-3β-ol, 24-ethylcholest-5-en-3β-ol, 24-ethyl-5α-cholestan-3β-ol) was very low (less than 20%) in depths of 143.8-70.2 cm but increased quickly to 50-75% in depths of 63.3-3.5 cm (Fig. 5, cf. Additional files Tables S2-S4).

3.1.4 Chlorophyll compounds and carotenoids

Chlorophyll compounds and carotenoids found in the MwS4C-1 sediment core from Lake Maruwanminami-ike are shown in Fig. 6. Chlorophyll *a*, pheophytin *a*, pyropheophytin *a*, zeaxanthin, lutein, pheophorbide b and pyropheophorbide b were detected mainly in depths of 72.5-110.4 cm with the most predominant peak at a depth of 24.2 cm as major chlorophyll derivatives and carotenoids. Chlorobactene was found in depths of 134.6-65.6 cm with the most striking peak at a depth of 67.8 cm (Fig. 6, cf. Additional file Table S5). These chlorophyl compounds and carotenoids were identified by comparing their retention times, UV–Vis spectra and mass spectra with those of authentic standards. A HPLC peak with its absorption maximum at 438 (as a shoulder), 463, and 494 nm was tentatively assigned as chlorobactene (Britton et al. 2004). These compounds are found in the previous studies from Lakes Skallen-oike (Matsumoto et al. 2010) and Oyako-ike (Matsumoto et al. 2014) in the Soya Coast region.

3.1.5 Microscopic observation of algae and cyanobacteria

Cyanophyceae of *Leptolyngbye* spp. and *Nostoc* sp., Chlorophyceae of *Cosmarium clepsydra* and/or *Staurastrum* sp. were identified in depths of 1.2, 28.8 and/or 58.7 cm in the MwS4C-01 sediment core (Table 2). Bacillariophyceae of *Humidophila australis, Psammothidium papilio*, *Anphora oligotraphenta, Diadesmis perpusilla, Navicula gregaria, Fragilariopsis curta, Fragilariopsis nana*, and *Navicula glaciei* were found in depths of 5.8, 28.8, 58.7, 65.6, 70.2, 81.7, 100.1 and/or 136.9 cm in the sediment core (Table 2).

3.2 Lake Maruwan-oike (Mw4C-01) sediment core

3.2.1 Lithology and geochronology

Visual observation of Lake Maruwan-oike (Mw4C-01) sediment core showed that the core was composed of laminated organic mud sediment (226-87 cm) overlain by globular organic mud sediment (87-72 cm), laminated organic mud sediment (72-35 cm), cyanobacterial sediment (35-28.5 cm), and cyanobacterial sediment with mosses (28.5 cm-surface). Soft X-ray photograph reflects the observation results of laminated and globular structures (Fig. 7). The bottom (226 cm)-50 cm were mainly light gray of thick structures, and 28.5 cm-surface were dark gray of cyanobacterial and moss structures.

The conventional and calibrated ages of TOC in the Mw4C-01sediment core is shown in Table 3. The calibrated age-depth relationship of the Mw4C-01 core revealed that the depths of 1.2, 21.9, 42.6, 61.0, 84.0, 97.8, 120.8, 141.5, 162.2, 180.6, 201.3 and 222.0 were 2,240±100 (2σ), 2,785±65, 3,115±165, 4,330±170, 4,500±180, 5,025±185, 5,085±185, 5,150±170, 5,415±145, 5,525±155, 5,600±150 cal BP, respectively. Age-depth relationships showed that sedimentation rate was decreased somewhat from the bottom to the top of the core. The age of the core bottom (226 cm) was linearly extrapolated to 5,700 cal BP (Fig. 7).

3.2.2 Elemental data (TC, TOC, TN, TIC and TS)

Figure 8 shows TC, TOC, TN, TIC and TS contents and TOC/TC, TOC/TN and TOC/TS weight ratios in the Mw4C-01 sediment core. TC contents throughout the core were 2-4% with peaks in depths of 182.9-162.2 cm and 35.7-26.5 cm. TOC contents were mainly 1-3% with a large peak at 26.5 cm. TN content of 0.4% at a depth of 224.3 cm was decreased somewhat from the bottom to the surface with fluctuation. Although TIC contents throughout the core were less than 1%, but large peaks were found in depths of 182.9-162.2 cm and 35.7-26.5 cm. TS contents were fluctuated largely ranging from 0 to 1.8% with higher contents in depths 201.5, 120.8-54.1 and 35.7-31.1 cm except for a few cases (Fig. 8, cf. Additional file

Table S6). The major elements of the Lake Maruwanminami-ike and Lake Maruwan-Oike sediments are, however, very similar as long as the correlation coefficients, but the correlations with C, N, and S are slightly different (Appendices (c), (d)).

3.2.3 Stable isotope ratios for carbon and nitrogen ($\delta^{13}C$, $\delta^{15}N$)

$\delta^{13}C$ and $\delta^{15}N$ results are shown in Fig. 9. $\delta^{13}C$ values in the Mw4C-01 sediment core varied from -25.3 to -13.1‰ with lower values less than -22‰ in depths of 224.3-222.0, 107.0, 102.4, 97.8 and 5.8 cm, and higher values greater than -16‰ with depths 28.8, 24.2 and 19.6 cm. $\delta^{15}N$ values in the core in depths of 222.0-125.4 cm were near constant (4-5‰), fluctuated with lower values of 1.3-5.4‰ in depths of 120.8-93.2 cm, and showed higher values of 5.5-7.0‰ in depths of 88.6-70.2, 40.3-21.9 and 1.2 cm (Fig. 9, cf. Additional file Table S7). Their isotope ratios are consistent with the previously reported results regards to Lake Maruwan-oike profiles (Takano et al., 2015). On the other hand, vertical distribution of $\delta^{13}C$ and $\delta^{15}N$ are largely different from Lake Skallen-oike (Matsumoto et al. 2010; Takano et al. 2012).

3.2.4 Chlorophyll compounds and carotenoids

Chlorophyll *a*, pheophytin *a* and/or pyropheophytin *a* in the Mw4C-01 sediment core were detected in depths of 224.3-26.5 cm as major chlorophyll *a* derivatives with a maximum peak at a depth of 176.0 cm (Fig. 10). Fucoxanthin, cis-diatoxanthin and zeaxanthin showed similar pattern with the chlorophyl derivatives. Pheophorbide b and pyropheophorbide b in the core were found in depths of 224.3-26.5 with large peaks at depths of 176.0 and 26.5 cm. Bacteriopheophorbide c and bacteriopheophorbide d ware found in depths of 107.0-79.4 and 47.2-28.8 cm with two striking peaks in depths of 88.6-79.4 and 28.8 cm (Fig. 10, cf. Additional file Table S8). Bacteriochlorophyll c and bacteriochlorophyll d identifications were based on the observed adsorption spectrum with Soret and Qy (red) maxima at 426 and 652 nm, respectively, and their ratio of 1.20 (Porra 2006). These bacterial pigments were not found in Lake Maruwanminami-ike as described above, although these compounds are reported in Lakes Skallen-oike (Matsumoto et al. 2010) and Oyako-ike (Matsumoto et al. 2014) in the Soya Coast region.

3.2.5 Microscopic observation of diatom

Total 65 diatom taxa were identified in the Mw4C-01 sediment core. Vertical distribution of diatom species showed zonation of diatom taxa with core depth (age), and were classified into marine taxa, brackish taxa and lacustrine taxa (Fig. 11; modified from Kang, 2018). Marine taxa such as *Thalassiosira australis*, *Fragilariopsis curta*, *Navicula glaciei* were distributed in coastal marine environment (222-40 cm). Brackish taxa, e.g. *Halamphora vyvermariana* were distributed in brackish lake environment (ca. 30 cm) which is transition period from marine to freshwater environment. Lacustrine taxa (ca. 20-0 cm), *i.e. Humidophilia* spp. and *Psammothidium papilio* were found in freshwater lake environment (Fig. 11).

4 Discussion

4.1 Lake Maruwanminami-ike

4.1.1 Sedimentary sequences and the timing of the transition of marine to brackish lake and to freshwater lake environment

Large reservoir effect of 1,230 cal BP of the MwS4C-01 sediment core (Fig. 3) is probably attributed the mixing of glacially eroded marine sediment from surroundings of the lake, because the lake area has been marine environment in the past In addition, Takano et al. (2015) reported that the subglacial weathering of silicate and aluminosilicate minerals in bedforms supplied significant levels of minerals, nitrogen, and relic carbon to subglacial meltwaters into the lake. They contain old and/or dead carbon, and thus cause large reservoir effect. The mean sedimentation rate was linearly calculated to be 0.389 mm/yr.

The transition periods from coastal marine to brackish lake, and to freshwater lake of Lakes Skallen-oike (Matsumoto et al. 2010) and Oyako-ike (Matsumoto et al. 2014) in the Soya Coast region are determined mainly based on the distribution of chlorobactene and/or bacteriopheophorbides derived from green sulfur bacteria (Pfennig 1967; Borrego and Garcia-Gil. 1994; Squier et al. 2002). 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). In this period, the lake being isolated from the coastal marine environment and becoming stratified as the isolated marine water was overlain by freshwater supplied from meltwater to the lake surface.

Furthermore, those environmental transitions and changes in primary producers associated with the glacial-isostatic uplift are supported by the other biogeochemical evidence from $\delta^{15}N$, molecular signatures (DGGE-16S rRNA, denaturing gradient gel electrophoresis with 16S ribosomal RNA gene analysis), and the major elements of sedimentary facies (e.g., Al_2O_3-SiO_2-Fe_2O_3 diagrams; Takano et al. 2012). The ongoing retreat of glaciers during and after the MHH, and ongoing isostatic uplift of the Soya Coast region accounts for this change as in the case of Lakes Skallen-oike and Oyako-ike.

In Lake Maruwanminami-ike sediment core (MwS4C-01), chlorobactene was found in depths of 134.6-65.6 cm with the most striking peak at a depth of 67.9 cm (Fig. 6). The MwS4C-01 sediment core in depths of approximately 70-0 cm was composed of mainly organic mud with lamination, while depths of 147-70 cm was mainly composed of diatomite with lamination (Fig. 3). TC, TOC, TN, TIC and TS contents, and TOC/TN and TOC/TS weight ratios in the core increased largely from a depth of approximately 70 cm to the surface (Fig. 4). This implies a change from marine to brackish/freshwater sediments in the core, since TS contents and TOC/TS ratios of marine sediments are generally much lower than those of freshwater lake sediments (Berner and Raiswell 1984; Sampei et al. 1997a, b). Marine diatoms such as *Fragilariopsis nana* and *Navicula glaciei* (Whitkowski et al. 2004) were found in depths of 70.2 and 65.6 cm, along with freshwater diatom of *Psammothidium papilio* (Kopalova et al. 2013) at a depth of 65.6 cm (Table 2). Marine diatoms are often dominated in brackish lakes in Vestfold Hills (Roberts and McMinn 1999; Verleyen et al. 2003). It is most likely, therefore, that the transition period of brackish lake environment (BLA) from coastal marine environment (CME) in the lake was between the depths of 72.5 (2,590 cal BP)-65.6 cm (2,500 cal BP, Fig. 3, Fig. 6).

Glacio-isostatic uplift rate of Lake Maruwaminami-ike was calculated by following equation. Lake altitude (mm asl)/(transition age of brackish lake (cal BP)−reservoir effect (cal BP)) = 11,200/(2,590-1,230)= 8.24 mm/yr. To our best knowledge, it is much higher than those of Lakes Skallen-oike (2.8 mm/yr, Matsumoto et al. 2010), Oyako-ike (2.2 mm/y, Matsumoto et al. 2014) and glacio-isostatic uplift rate within Skallen and Skarvesnes (3.2 mm / y, r^2 = 0.98; Takano et al., 2012). A first-order linear model based on the radiocarbon dating from *L. elliptica* (data from Miura et al. 1998b) showed 3.9 mm/y (r^2 = 0.68) by the compilation (the supplementary figure 3 in the Takano et al. 2012).

4.1.2 Coastal marine environment (CME, 147-72.5 cm, 5,010-2,590 cal BP)

The MwS4C-01sediment core in depths of 147-72.5 cm was mainly composed of diatomite with lamination (Fig. 3). TOC and TN contents are proxy of biomass and biological production in lake sediment cores (e.g. Matsumoto et al. 2003, 2010, 2012). TOC and TN contents ranging from 0.041 to 2.60% with an average of 1.53±0.56% (standard deviation) and from 0.11 to 0.0.47% with an average of 0.24±0.08% in the CME (147-72.5 cm depth), respectively, were considerably low as compared with those in the BLA (72.5-65.6 cm depth) and freshwater lake environment (FLE, 65.6-0 cm) as discussed below (Table 3, Fig. 4). These results showed low primary productivity in the CME as in the case of Lakes Skallen-oike (Matsumoto et al. 2010) and Oyako-ike (Matsumoto et al. 2014).

The compositions of n-C_{17} alkane and diploptene and long-chain n-alkanoic acids (C_{20}-C_{36}) in depths of 143.8-72.5 cm were very low less than 10%, while short-chain n-alkanoic acid (C_{12}-C_{19}) in these depths were relatively high with near constant of 70% (Fig. 5, cf. Additional files Tables S2-S3). C_{28} sterols (24-methylcholetsa-5,22-dien-3β-ol, 24-methylcholest-5-en-3β-ol, 24-methyl-5α-cholestan- 3β-ol) were very high (58.9-82.6%) in depths of 143.8-74.8 cm of the CME (Fig, 5, cf. Addiotional file Table S4). C_{28} sterols (mainly 24-methylcholest-5-en-3β-ol) are often major sterols of diatoms (Volkman et al. 1998; Matsumoto et al. 2003, Rampen et al. 2010) reflecting probably dominance of diatom assemblage in the CME. Marine diatom assemblage of *Amphora oligotraphenta, Diadesmis perpusilla, Nabicula gregaria, N. glaciei, Fragilariopsis curta* and *F. nana* (Gersonde and Zielinski 2000; Cramer et al. 2003; Pike et al. 2009) were distributed in these depths (Table 2).

Small amounts of chlorophyll *a*, pheophytin *a*, pyrophephytin *a*, were detected in depths of 143.8-72.5 cm (Fig. 6). They are commonly distributed in photosynthetic organisms (Tani et al. 2009; Matsumoto et al. 2010). Interestingly, chlorobactene was distributed in depths of 134.6-74.5 cm at small amounts (Fig. 6, cf. Additional file Table S5). This result strongly suggests the presence of green sulfur bacteria in anoxic conditions of the euphotic bottom water because the coastal marine depression water is probably stagnant during the glacio-isostatic uplift of the basin.

4.1.3 Stratified brackish lake environment (BLE, 72.5-65.6 cm, 2,590-2,500 cal BP)

TOC and TN contents in the BLE (72.5-65.6 cm depth) were 2.39±2.20% and 0.29±0.19%, respectively, which are considerably higher than those in the CME (Table 4). Small amounts of photosynthetic pigments of chlorophyll *a*, pheophytin *a*, pyropheophytin *a*, pheophorbide b and pyropheophorbide b were found in these depths. Of special interest is the occurrence of chlorobactene with very high concentration (3,830 μg/L) at a depth of 67.9 cm (Fig. 6). The chlorobactene can be interpreted by the presence of green sulfur bacteria as an indicator for 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; Matsumoto et al. 2010).

Green sulfur bacteria are presumably contributed relatively high TOC and TN contents. In this period, Lake Maruwanminami-ike was isolated from the sea and becoming stratified as the isolated marine water was overlain by freshwater supplied from glacial meltwater to the lake surface as in the case of Lakes Skallen-oike (Matsumoto et al. 2010) and Oyako-ike (Matsumoto et al. 2014). Diatoms of *Amphora oligotraphenta, Diadesmis perpusilla, Nabicula gregaria N. glaciei, Fragilariopsis curta* and *F. nana* (Whitkowski et al. 2004) were distributed in this layer as in the case of the CME (Table 2). Verleyen et al. (2017) reported that marine diatom species could survive in saline conditions in Lake Kobatchi-ike in Skarvsnes for hundreds of years. Also, marine diatoms are often dominated in brackish lakes in Vestfold Hills (Roberts and McMinn 1999; Verleyen et al. 2003).

4.1.4 Freshwater lake environment (FLE, 65.6-0 cm, 2,500-1230 cal BP)

The MwS4C-01sediment core in depths of 65.6-0 cm was mainly composed of organic mud with lamination (Fig. 3). TOC and TN contents in the FLE (65.6-0 cm depth) were 5.75±4.75% and 0.67 ±0.50%, respectively, which are much higher than those in the CME and the BLE. Biological production in the FLE is much higher than those in the CME as in the case of Lake Skallen-oike (Matsumoto et al. 2010), Lake Oyako-ike (Matsumoto et al. 2014), Pup Lagoon (Verleyen et al. 2004) and Lake Reid (Hodgson et al. 2005) in the Larsemann Hills, East Antarctica. TIC% in the FLE/CME ratio is very high with 10.3 (Table 4) which can be explained by the presence of carbonate (e.g. Takano et al. 2015). TS% and TOC/TS ratio of the FLE/CME value were 1.40 and 3.81 times high, respectively, reflecting typical freshwater environment (Table 4; Berner and Raiswell 1984; Sampei et al. 1997a, b).

Abundance of n-C_{17} alkane in depths of 40.3-8.1 cm in the MwS4C-01 sediment core (Fig. 5) may be attributed to cyanobacteria and green algae because it is often most predominant *n*-alkane in these organisms (Weete, 1976; Matsumoto, 1993). High percentages of long-chain *n*-alkanoic acids (9.8-38.9%) in depths of 63.3-3.5 cm of the FLE as compared with those in depths of 143.8-72.5 cm in the CME (147-

72.5 cm) may reflect the contribution of green algae such as *Cosmarium clepsidora* and *Staurstrum* sp. (Table 2, Matsumoto et al. 2010). Branched (*iso* and *anteiso*) alkanoic acids were predominant in depths of 49.5-8.1 cm in the FLE as compared with those in depths of 143.8-72.5 cm in the CME reflect the abundance of bacteria (Fig. 5; O'Learry et al. 1982; Reddy et al. 2002, 2003a,b). High percentages of diploptene in depths of 49.5-8.1 cm are consistent with high bacterial contribution (Fig. 5; Prahl et al. 1992; Elvert et al. 2001).

C_{29} sterols (mainly 24-ethylcholest-5-en-3β-ol) showed high percentage in the FLE (52.7-68.1%) and low percentages in the CME (less than 24%, Fig. 5). Although 24-ethylcholest-5-en-3β-ol is commonly used as a biomarker of vascular plants in the mid and lower latitudes, this sterol is widely distributed in Antarctic lake waters and sediments including the Soya Coast region as most predominant sterol in spite of the absence of vascular plants (Matsumoto et al. 1982, 1993, 2006; Matsumoto 1993; Volkman et al. 1998). Predominance of 24-ethylcholest-5-en-3β-ol in the FLE is probably derived from green algae and cyanobacteria (Matsumoto et al. 1982, 1993; Matsumoto, 1993) which are much abundant than those of diatoms. C_{27} sterols (mainly cholest-5en-3β-ol) are derived from microalgae including diatoms (Matsumoto et al. 1982, 2006; Volkman et al. 1998; Rampen et al. 2010), though C_{27} sterols in the FLE (63.3-3.5 cm depth) are somewhat higher than those in the CME (143.8-70.2 cm depth). It is much likely that the contribution of green algae is greater than diatoms (Fig. 5).

Ubiquitous photosynthetic pigments (chlorophyll *a*, pheophytin *a* and pyropheophytin *a*), pheophorbide b, and pyropheophorbide b) and a carotenoid (zeaxanthin) were found in the FLE (Fig. 6). These pigments are derived from Cyanophyceae of *Leptolyngbya* spp., Chlorophyceae of *Cosmarium clepsydra* and *Straurstrum* sp. and Bacillariophyceae of *Amphora oligotraphenta, Diadesmis perpusilla, Navicula gregaria, Fragilariopsis curta* and *F. nana* in the FLE (Table 2).

Very high TOC and TN contents in the FLE are mainly due to the contribution cyanobacteria and green algae rather than diatoms as evidenced by the abundance of 24-ethylcholest 5-en-3β-ol.

4.2 Lake Maruwan-oike

4.2.1 Sedimentary sequences and the timing of the transition of marine to brackish lake and to freshwater lake environments

Very large reservoir effect of 2,230 cal BP in the Mw4C-01 sediment core is probably attributed to the glacially eroded marine sediments deposited in the past and glacial erosion of bed rocks as in the case of L. Maruwanminami-ike. Average sedimentation rate was calculated to be 0.649 mm/y, although sedimentation rates were gradually decreased from the core bottom to the surface (Fig. 7). The sedimentation rate of the Mw4C-01sediment core is, however, 1.67 times higher than that of the MwS4C-

01 sediment core from L. Maruwanminami-ike. Glacially eroded sediments of Lake Maruwan-oike are much greater than those of L. Maruwanminami-ike.

The transition period of CME, BLA and FLE are not clear in the visual observation of sedimentary facies of the Mw4C-01 sediment core. Vertical distribution of TOC, TN and TS contents (Fig. 8) showed no increasing trends with the transition from the CME, the BLA and the FLE as observed in Lake Maruwanminami-ike, and previously reported in Lakes Skallen-oike and Oyako-ike (Matsumoto et al. 2010, 2014; Takano et al. 2012).

Seto et al. (2002) reported the transitions from the CME to the BLE and to the FLE using Mw-4 sediment core (length 187 cm, water depth 9.8 m) from Lake Maruwan-oike. The vertical profile of the core is considerably different from our Mw4C-01 core. The CME (187-68 cm) was composed of diatomite mud with benthic forminifera *Trochammina antarctica*. The BLE was characterized by cyanobacterial mud with fine (<1 mm) laminated black-dark olive sediment formed in the anoxic conditions of depths of 68-60 cm with bottom ages of 3,430 yr BP without calibration of marine sediment age (-1,300 yr) and reservoir effects (no surface age datum). The FLE was composed of cyanobacterial mud with fine lamina (<1 mm) containing aquatic moss (*Bryum pseudotriquetrum*, Imura et al. 2003).

Here we estimated the transition period by the occurrence of bacteriopheophorbide c and bacteriopheophorbide d in depths of 107.0-79.4 and 47.2-28.8 cm with two large peaks (Fig. 10, cf. Additional file Table S8). It is most probable that first bacteriopheophorbide c and bacteriopheophorbide d peaks are due to green sulfur bacteria in the anoxic photic zone of the CME as in the case of Lake Maruwanminami-ike as discussed above. Diatom assemblage revealed the zonation of marine, brackish and freshwater taxa in depths of 226-35, 35-23 and 23-0 cm, respectively (Fig. 11). Indeed, *Navicula cancellate* (Ognjanova-Rumenova and Buczko 2015) and *N. phyllepta* (Vanelslander et al. 2009) are marine and/or brackish species, and *Halamphora vyvermaniana* (Van de Vijver et al. 2014) is distributed in freshwater environment (Fig. 11). These diatom assemblages support strongly changes from the CME to the BLE. The δ^{13}C values in depths of 28.8-19.6 cm were relatively high ranging from -22.3 to -12.9‰ with an average of -16.8±4.2‰ (Table 5) which reflect probably cyanobacteria and mosses in the FLE as in the case of Lake Skallen-oike (Matsumoto et al. 2010). The transition periods from the CME to the BLA and to the FLE are, therefore, occurred in the second peak of bacteriopheophorbide c and bacteriopheophorbide d in depths of 47.2-28.8 cm in the lake. It is consistent with the result of Takano et al. (2015). They reported that the transition ages from marine to freshwater lake are between 3,382 and 3,560 cal BP (median age 3,371 cal BP) in depths of 49-46 cm based on vertical profile of major elements (SiO_2, Fe_2O_3, Al_2O_3, TiO_2, CaO, K_2O) and microflora differences of DGGE (denaturing gradient-gel electrophoresis) in Lake Maruwan-oike sediment core (Mw5S, core length 156 cm).

Glacio-isistatic uplift rate of Lake Maruwan-oike was calculated by the same method of Lake Maruwanminami-ike. 8,000 mm /(3,190 cal BP-2,220 cal BP) = 8.25 mm/y. This result is consistent with the result of Lake Maruwanminami-ike (8.24 mm/y). Crustal uplift of these adjacent lakes occurred at the same time. They are much higher than those of Lakes Skallen-oike (2.8 mm/y; Matsumoto et al. 2010) and Oyako-ike (2.2 mm/y; Matsumoto et al. 2014). The differences of these crustal uplift rates were discussed below (4.3).

4.2.2 Coastal marine environment (226-47.2 cm, 5,700-3,190 cal BP)

The soft X ray photograph of the Mw4C-01 sediment core in depths of 226-47.2 cm (Fig. 7) showed mainly light gray with lamination or globular structures, and consistent with low TOC and TN contents. High TIC peak was found in depths of 182.9-162.2 cm which is probably contribution of sea shelf such as bivalve fossils in Rundvagshetta region (Fig. 8; Hirakawa and Sawagaki, 1998; Takano et al. 2015).

TOC and TN contents ranging from 0.82 to 3.82% with an average of 2.17±0.56% and from 0.22 to 0.67% with an average of 0.43±0.10% in the CME (224.3-47.2 cm depth), respectively, were similar to those in the BLA (47.2-28.8 cm depth), but considerably high as compared with those in the FLE (28.8-0 cm depth) as discussed below (Table 6, Fig. 8). These results reflect the low primary production in the FLE which are very different from those in the Lake Maruwanminami-ike discussed above.

Antarctic marine sediments influenced by phytoplankton have $\delta^{13}C$ values lower than -22% (Boutton 1991). In the Mw4C-01 sediment core, $\delta^{13}C$ and $\delta^{15}N$ values in depths of 224.3-47.2 cm ranged from -23.7 to -18.8‰ with an average of 21.1±1.1 (standard deviation, and from 1.3 to 7.0 with an average of 4.2±1.3‰, respectively (Fig. 9, Table 5). The $\delta^{13}C$ values were slightly higher than that of present Antarctic marine sediments, while $\delta^{15}N$ values were somewhat lower than the range of diatom-bound $\delta^{15}N$ in the Holocene sediment cores from the Antarctic Ocean (Robinson and Sigman 2008). These results suggest the contribution of terrestrial organic matter inputs as in the case of Lake Skallen-oike (Matsumoto et al. 2010).

Chlorophyll *a*, pheophytin *a* and pyropheophytin *a* are commonly distributed in photosynthetic organisms (Tani et al. 2009; Matsumoto et al. 2010). *Cis*-diatoxanthin is distributed in green algae, diatom and cyanobacteria, but pheophytin *b* and pyropheophytin *b* are distributed in green algae, brown algae and vascular plants. These pigments are come from green algae, because no brown algae and vascular plants are 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).

The presence of bacteriopheophorbide c and bacteriopheophorbide d in depths of 107.0-79.4 cm (Fig. 10; 4,700-4,070 cal BP) strongly suggests the presence of green sulfur bacteria in the photic anoxic environment caused by stagnant bottom seawater in the depression of shallower coastal marine environment due to glacio-isostatic uplift.

Marine diatoms of *Thalassiosira australis*, *Fragilariopsis curtca*, *F. nana/cyrindrus*, *Navicula directa* and *N. glaciei, etc.* were distributed in depths of 226-49.6 cm of the Mw4C-01 sediment core (Fig. 11). These diatom species are generally related to sea ice and ice edge environment (Cremer et al. 2003; Pike et al.

2009). The marine environment is covered with sea ice. *T. australis* and *T. antarctica* are associated with relatively open water of marginal ice edge environments (Taylor et al. 1997; Zielinski and Gersonde 1997).

4.2.3 Stratified brackish lake environment (BLE, 47.2-28.8 cm, 3,190-2,890 cal BP)

Laminated organic mud sediment (47.2-35 cm) and cyanobacterial sediment (35-28.5 cm) were distributed in this layer. TOC and TN contents ranged from 1.34 to 3.06% with an average of 1.95±0.57% and from 0.22 to 0.50% with an average of 0.32±0.09%, respectively (Table 6). Biological production and biomass in the BLE are somewhat lower than those in the CME.

The $\delta^{13}C$ and $\delta^{15}N$ values in depths of 47.2-28.8 cm of the Mw4C-01 sediment core ranged from -21.5 to -12.9‰ with an average of -19.2±3.2‰ and from 4.6 to 6.1‰ with an average of 5.6±0.6‰, respectively (Fig. 9, Table 5). These values reflect probably the contribution of terrestrial organic matter and green sulfur bacteria in the BLE, because $\delta^{13}C$ values of green sulfur bacteria (*Prosthecochloris* sp.) are -19.3 - -22.9‰ with an average of -21.5±1.2‰ (Zyekun et al. 2009) and not distinguish with those of terrestrial organic matter input. Ubiquitous photosynthetic pigments of chlorophyll *a*, pheophytin *a* and pyropheophytin *a* in the BLE were very small, but considerable amounts of pheophorbide b and pyropheophorbide b were detected in the BLE (Fig. 10). Cyanobacteria and diatoms are important primary producer in this layer, but red algae are absent in the lake. The occurrence of bacteriopheophorbide c and bacteriopheophorbide d reflects probably the presence of green sulfur bacteria as an indicator for the formation of a stratified water column with a chemocline and an anoxic (sulfidic) layer at the bottom of photic zone. The L.ake Maruwan-oike basin being isolated from the sea and becoming stratified as the isolated marine water was overlain by freshwater supplied from meltwater to the lake surface as in the case of Lake Maruwanminami-ike as discussed above.

4.2.4 Freshwater lake environment (FLE, 28.8-0 cm, 2,890-2,240 cal BP)

This sediment layer is composed of cyanobacterial sediment with mosses (28.5 cm-surface). Soft X-ray of these layer were dark gray of cyanobacterial and moss structures (Fig. 7). TOC contents ranging from 0.12 to 6.49% with an average of 1.36±1.66% in the FLE (28.8-0 cm), were considerably lower than those in the CME (224.3-47.2 cm) and the BLA (47.2-28.8 cm, Table 6), and much lower than those in the FLE of L. Maruwanminami-ike (9.11±6.84%) as discussed above and those in Lake Skallen-oike (11.7±3.3%, Matsumoto et al. 2010) and Lake Oyako (6.84±3.33%, Matsumoto et al. 2014). These results showed very low biological production and biomass in the FLE mainly due to low distribution of photosynthetic organisms of cyanobacteria, green algae, diatoms and mosses with continuously supplied large amounts of glacially eroded bedforms as evidenced by large reservoir effect. Very low TOC and TN contents in depths of 15.0-1.2 cm may be significant contribution of glacially eroded sediments (Fig. 8).

High TIC peak in depths of 30-28 cm is probably contribution of carbonate as in the case of Lake Maruwanminami-ike discussed above (Fig. 8). It is likely that very low TS contents in the FLE are attributed to the influence of marine sediments in the past and/or eroded metamorphic base rocks.

The $\delta^{13}C$ and $\delta^{15}N$ values in depths of 28.8-1.2 cm of the sediment core ranged from -30.1 to -12.9‰ with an average of -20.1±5.6‰ and from 2.5 to 7.9‰ with an average of 5.5±0.6‰, respectively (Fig. 9, Table 5). These values varied largely and reflect probably cyanobacteria and mosses with complex sedimentation.

Chlorophyll *a* and their derivatives and carotenoids were almost absent in the FLE (Fig. 10). The diatom assemblage in the FLE is composed mainly of Antarctic endemic freshwater diatom taxa, *Humidophila australis* and *Psammothidium papilio* in the FLE of Lake Maruwan-oike (Fig. 11, Sabbe et al. 2003). These two diatom species are major diatoms in the FLE of Lake Maruwanminami-ike as discussed above (Table 2).

4.3 High glacio-isostatic uplift rates of Rundvågshetta lakes

Here we discuss high glacio-isostatic uplift rates of 8.24 and 8.25 mm/yr in Lakes Maruwanminami-ike and Maruwan-oike, respectively. They are much higher than those in raised beach deposits from the northwest side (N940114-3A. 3.7 mm/yr; d940112-3B, 2.5 mm/yr) of Lake Maruwan-oike and from the northwest sites of some hundreds of meters from the lake (c940112-3, 2.9 mm/yr; M940112-4, 2.9 mm/yr; Fig. 2, Table 7). They were calculated by altitude and corrected marine age (-1,300 yr) data of Hirakawa and Sawagaki (1998). Furthermore, they are much higher than our calculated datum of 2.3 mm/yr of Mw5S sediment core from Lake Maruwan-oike reported by Takano et al. (2015). Their big discrepancy is ascribed to the difference of age pattern of our Mw4C-01core and Mw5S core. Takano et al. (2015) reported ages of the core top (0-2 cm) and 6-8 cm depths of the Mw5S core were 1,350 and 3,950 cal BP, respectively, whereas ages of the core top (0-2.4 cm) and 20.7-23.1 cm depths of our Mw4C-01 core were 2,240 and 2,785 cal BP, respectively (Table 3). Takano et al. (2015) explained the occurrence of hiatus at the core top of the Mw5S, while no hiatus was found in our Mw4C-01core.

It is much likely that the sedimentation in Lake Maruwan-oike is very different in the coring sites, because the Mw4C-01 and Mw5S sediment cores were taken in water depths of 15.7 m and 20.2 m (Takano et al. 2015), respectively. Besides, vertical profile of Mw-4 sediment core from Lake Maruwan-oike (water depth 9.8 m; Seto et al. 2002) was considerably different from the Mw4C-01sediment core. The maximum depth of Lake Maruwan-oike is 37 m (Imura et al. 2003) and thus coring depths are slopes of the lake. Slumping and reworks may be occurred in a certain place and form hiatus in the slopes. If core top of the Mw5S was omitted and extraporated age of core top was obtained ca.2,500 cal BP. Glacio-isostatic uplift rate can be, therefore, calculated to be 8,000/(3,560-2,500) = 7.5 mm/yr which is consistent with our results. These glacio-isostatic uplift rates of Lakes Maruwanminami-ike and Maruwan-oike are much higher than other isolated basins and raised beaches in the Soya Coast region (Table 7).

In order to explain these difference of the uplift rate estimation, further researches using new sediment cores from the deepest sites of the Rundvågshetta lakes other than slopes. It is possible that glacio-isostatic uplift rates of raised beach sediments and isolated basins are different in the Rundvågshetta lakes, because lake sediments are supplied from glacially eroded marine sediments and bed rocks evidenced by very high reservoir effects. Further studies on chronological models and high-precision GPS survey (e.g. Ohzono et al. 2006; Argus et al., 2014) will have to be required with re-assessments of relic carbon flux from sub-glacial meltwater for refining the calendar age reconstruction (e.g. Sawagaki and Hirakawa, 1997; Wingham et al. 2006; Takano et al. 2015, cf. insight from $^{10}Be/^{9}Be$ profiles from Sproson et al., 2021).

4.4 Paleoenvironmental change in the Soya Coast region and in East Antarctica

Since the LGM glacial retreat and subsequent crustal uplift has been occurred in Antarctica including the Soya Coast region. Kawamata et al. (2020) studied ^{10}Be and ^{26}Al radio isotopes for ground surface exposure dating and demonstrated that the ice sheet completely covered the highest peak of Skarvsnes (400 m asl.) prior to ca. 9 ka and retreated eastward by at least 10 km during the early to middle Holocene (ca. 9 to 5 ka BP). The timing of the abrupt ice-sheet thinning and retreat is consistent with the intrusion of modified Circumpolar Deep Water (mCDW)into deep submarine valleys in the Lützow-Holm Bay.

In the previous study on raised beach deposits at higher altitudes greater than 20 m asl are reported in the Ongul Islands (35.0 m), Langhovde (27.4 m), Skarvsnes (39.0 m), Skallen (32.3 m), Skallevikhalsen (23.9 m) and Rundvågshetta (23.0 m, Omoto, 1977) in the Soya Coast region as well as Cape Hinode (30-35 m) in the Prince Olav Coast (Yoshida and Moriwaki, 1979, Fig. 1), but no further scientific confirmation including dating was done for these higher altitude samples until today. Fossil marine organisms mainly molluscs, foramiminifers and serpuloid tubes in beach deposits are distributed below 20 m asl (Hayashi and Yoshida, 1994; Igarashi et al. 1995a,b; Hirakawa and Sawagaki,1988; Miura et al. 1998a,b, 2002).

Miura et al. (1998a,b, 2002) demonstrated based on the two groups formed in Late Pleistocene (30,000-46,000 yBP), and in the middle Holocene (3,000-7,200 yBP) in the Ongul Islands, Langhovde and Skavsnes. They concluded that East Antarctic Ice Sheet (EAIS) retreated from the northern Soya Coast and a transgression occurred prior to the LGM, and the EAIS had not re-advanced over the beach of the northern Soya Coast region even during the LGM, as evidenced by the existence of 30,360-46,000 yr BP *in situ* fossil shells. Holocene transgression and subsequent retreat had been occurred in the northern and southern Soya Coast regions during the Holocene. Miura et al. (1998a,b) showed high sea level had reached at least 20 m asl without taking isostatic rebound into consideration (Fig. 1, see Table 7).

Table 7 summarizes typical RSL results, transition ages and glacio-isostatic uplift rates during the Holocene in the Soya Coast region and some related areas in East Antarctica. We use mainly AMS ^{14}C dating data and some selected β ray dating data of ^{14}C ages which are consistent with AMS ^{14}C dating data. Because older fossils occur very close proximity to younger fossils in beach deposits of the Ongul Islands and Langhovde north, certain ^{14}C ages determined by β ray dating method, which requires relatively large amounts of samples, were obtained by the mixture of old and younger fossils especially approximately 10-28 kyr BP samples (Hayashi and Yoshida, 1994; Igarashi et al. 1995b; Miura et al.1998b).

Verleyen et al. (2017) provided new data on deglaciation history and develop new RSL curves along an 80 km transect in the Lützow Holm Bay region. The minimum radiocarbon age for regional deglaciation is ca.11,240 cal. yr BP (no marine age subtraction of -1,300 yr) on West Ongul Island with progressively younger deglaciation ages (from Langhovde to Skarvsnes and Skallen) approaching the main regional ice outflow at Shirase Glacier (Fig. 1, Table 7). AMS ^{14}C dates of fossils in raised marine deposits and data from isolation basins have further refined this record similar RSL curves for the Ongul Islands, Langhovde and Skallen, but a strikingly different RSL curve for Skarvsnes that sediment cores from an isolation basin in combination with ^{14}C dates of marine fossils deposited in the sill revealed a RSL high stand of 32.7 m around 4,400 cal BP (Verleyen et al. 2017). The difference in RSL high stand of Langhovde is tentatively linked to neotectonic processes such as reactivation of a local fault in Skarvsnes (Verleyen et al. 2017). The reconfirmation of the evidence of marine fossils at higher altitude and reactivation of a local fault will be necessary.

Transition ages from marine to lake environments of 11 sediment cores in 8 lakes (isolated basins) were discussed for the Ongul Islands (Lakes Yumi-ike and Oike), Skarvsnes (Lakes Oyako-ike, Mago-ike and Kobati-ike), Skallen (Lake Skallen-oike) and Rundvagshetta (Lakes Maruwanminami-ike and Maruwan-oike; Fig. 1, Table 7). The RSL and transition age of each lakes are as follows: Yumi-ike (10 m asl. 4,370 yr BP), Oike (13, 5,720), Oyako-ike (2.37, 1,060), Oyako-ike (2.37, 1,080), Mago-ike (1.5, 1,380), Kobati-ike (28, 2,120), Skallen-oike (10, 3,440), Skallen O-ike (9.64, 2,940), Maruwanminami-ike (11.2, 1,380), Maruwan-oike (8.0, 970), Maruwan-oike (8.0, 3,471; Table 7). Altitudes (m asl) of all raised beach data are correlated with transition ages with a correlation coefficient of r^2 = 0.291 (Fig. 12A). Transition age of Lake Kobati-ike was small in spite of high altitude. Maruwanminami-ike and Maruwan-oike were high reservoir effect as discussed above. The transition ages of all raised beaches and isolated basins (Table 7) ranged from 970 to 9,290 yr BP with an average of 3,660±1,520 yr BP (standard deviation) suggesting that major warm periods in the Soya Coast region are the middle Holocene so-called the MHH. It is consistent with that the warm period of the Lützow-Holm Bay region is 4,800-3,000 yr BP (Verleyen et al. 2011).

Holocene RSL, transition ages and crustal uplift rates in East Antarctica have been reported in the Vestfold Hills, Larsemann Hills, Windmill Islands, Bunger Hills and Scott Coast (Table 7). Zwartz et al. (1998) studied Organic L. (3.5 m asl, 3,465 yr BP), Watts L. (4.3, 3,630), Highway L. (7.7, 4,755), Druzhby L. (8.0, 5,720), Anderson L. (8.4, 5,505), Ace L. (8.8, 4,550) in Vestfold Hills. They subtracted 1,300 years for marine reservoir correction. We showed here mean ages. Verleyen et al. (2020) summarized Larsemann Hills (isolated basin; 8 m asl, 7,000-7,600 yr BP), Windmill Islands (raised beach; 30, 6,900), Bunger Hills (raised beach; 8, 5,000-5,600 yr BP; Figurmoye L. (isolated basin; 11.2, 5,000-8,000) and Scott Coast (raised beach; 32, 6,600; Table 7). These transition ages are somewhat greater than those in the Soya Coast region. According to the warm periods of Verleyen et al. (2011), Larsemann Hills (7,300-5,400 yr BP) and Bunger Hils (5,500-2,000 yr BP) are in the range of the transition ages, while those in Vestfold

Hills (8,000-5,500 yr BP) are somewhat higher than the transition ages, but Windmill Islands (4,000-2,000 yr BP) is much lower than the transition ages. Further studies are required for the relationships between Antarctic regional warm periods and the transition ages.

4.5 Glacio-isostatic uplift rates

Omoto (1977) studied raised beach deposits and found glacio-isostatic uplift rates of the Ongul Islands, Langhovde and Skarvsnes less than 6,000 yr BP are 2.7 mm/yr, no data and 2.6 mm/yr, respectively. Crustal uplift rates of submerged ice-free areas to RSL seems to be at least 2.5 mm/yr on the average during the last 6,000 years (Yoshida and Moriwaki, 1979, Table 7).

Miura et al. (1998a,b, 2002) studied the stratigraphy of raised beaches in the sediment layers of excavated trenches and provide sample elevation and AMS ^{14}C age, but no crustal uplift rates are given. We calculated marine reservoir corrected age (-1,300 yr) and glacio-isostatic uplift rates based on data of Miura et al. (1998a,b, 2002, Table 7). Older group formed in Late Pleistocene (30,000-46,000 yBP) are found in East Ongul Island and part of Langhovde north. Their glacio-isostatic uplift rates were very low less than 0.35 mm/yr. Younger groups formed in the middle Holocene of Langhovde north, Langhovde south and Skarvsnes were ranging from 0.72 to 3.02 mm/yr with an average of 1.97±0.71(standard deviation)mm/yr, 0.39 to 3.36 mm/yr with an average of 1.47±1.2 mm/yr and from 1.25 to 2.81 mm/yr with an average of 2.10± 0.49 mm/yr, respectively (Table 7).

Glacio-isostatic uplift rates of lakes and ponds of isolated basins were studied in the Soya Coast region. Here we calculated crustal uplift rates of Lakes Yumi-ike, O-ike, Mago-ike and Kobachi-ike using data of Verleyen et al. (2017) and its supplementary tables (Table 7).

Yumi-ike: 10,000 mm/(4,830 cal BP - 460 cal BP) = 2.3 mm/yr

O-ike: 13,000 mm/(5,720 cal BP – 0 cal BP) = 2.3 mm/yr

Mago-ike: 1,500 mm/(1,380 cal BP – 0 cal BP) = 1.1 mm/yr

Kobachi-ike: 28,000 mm/(2,800 cal BP – 680 cal BP) = 13.2 mm/yr

Glacio-isostatic uplift rates of Lakes Yumi-ike (10 m asl) and O-ike (13 m asl) in the Ongul Islands were 2.3 mm/yr and 2.3 mm/yr, respectively. Those of Lake Oyako-ike (2.37 m asl) in Skarvsnes are 3.2 mm/yr (Takano et al. 2012) and 2.2 mm/yr (Matsumoto et al. (2014). Lakes Mago-ike (1.5 m asl) and Kobachi-ike (28 m asl) in Skarvsnes were 1.1 and 13.2 mm/yr, respectively. Very high crustal uplift rate of Lake Kobachi-ike is not clear, though it is linked with high crustal uplift rate of raised beach data (7.4 mm/yr; Table 7).

Glacio-isostatic uplift rates of Lake Skallen-oike (10 or 9.64 m asl) are 2.8 mm/y (Matsumoto et al. 2010) and 3.2 mm/y (Takano et al. 2012). Calculated crustal uplift rate of *L. eliptica* in raised breach deposit from L. Skallen-oike (12 m asl, 4,720 yr BP; Igarashi et al. 1995a,b) is 2.5 mm/y which is similar to those of lake sediment core results (Table 7). These uplift rates are consistent with present uplift rates estimated by bedrock GPS (2.3±0.3 mm/yr) and Very Long Baseline Interferometry at Syowa Station in East Ongul Is. (VLBI, 4.6±2.2 mm/y; Kaminuma 2008).

Glacio-isostatic uplift rates of raised beaches and isolated basins in the Soya Coast region ranged from 0.19 to 4.40 with an average of 2.0±0.92 mm/yr except for 4 higher values (7.4, 13.2,8.2, 8.3 mm/yr, Table 7). The glacio-isostatic uplift rates of the Soya Coast region are similar to those estimated in the Lambert Glacier region (1.8-1.9 mm/yr; Verleyen et al. 2005), Vestfold Hills (1.0-1.9 mm/yr; Zwart et al. 1998), Larsemann Hills (1-1-1.14 mm/yr; Verleyen et al. 2005), Bunger Hills (2.2-1.4 mm/yr; Adamson and Colhoun, 1992; Verkulich et al. 2002), but lower than Scott Coast (4.8 mm/y; Hall et al. 2004; Table 7).

The altitudes of raised beaches in the Soya Coast region are correlated with transition ages as discussed above (Fig. 1). The AMS ^{14}C ages of altitudes less than 20 m are mainly obtained from marine fossils of *L. elliptica* in the sediment layers of excavated trenches (Miura et al. 1998a,b, 2002). Their ages reflect probably coastline in the past because glacial retreat cause rising beaches continuously. Marine organism of *L. elliptica* fossilized due to changing from marine to terrestrial environment. Glacio-isostatic uplift rates of raised beaches are correlated with altitudes with a correlation coefficient of r^2 = 0.724 (Fig. 12B). Increasing crustal uplift rates with altitudes reflect continuous crustal uplifts in the Soya Coast region.

5 Conclusions

We studied Holocene paleolimnological changes in Rundvågshetta lakes (Maruwanminami-ike and Maruwan-oike) in the Soya Coast region and discussed in paleoenvironmental changes, marine to terrestrial transition ages and glacio-isostatic uplift rates in East Antarctica.

(1) Ages of the Maruwanminami-ike core (MwS4C-01, core length 147 cm) and Maruwan-oike (Mw4C-01, core length 226 cm) ranged from 1,230-5,010 cal BP and 2,240-5,700 cal BP, respectively. Reservoir effects of the Rundvågshetta lakes were very high which may be due to the influence of organic matter in glacially eroded sediments containing dead carbon, marine sediments and/or glacially eroded base rocks.

(2) Average sedimentation rate of Lake Maruwanminami-ike (0.389 mm/yr) was much lower than that of Lake Maruwan-oike (0.649 mm/yr). Large amount of sedimentary matter was supplied for the latter.

(3) Average glacio-isostatic uplift rates of Lakes Maruwanminami-ike and Maruwan-oike determined by sedimentary facies, green sulfur bacterial biomarkers and diatoms were estimated to be 8.24 and 8.25 mm/y, respectively.

(4) Coastal marine environment: Maruwanminami-ike (147-72.5 cm, 5,010-2,590 cal BP) and Maruwan-oike (226-47.2 cm, 5,700-3,190 cal BP) were characterized by low biological production with predominance of diatoms.

(5) Transition period of stratified brackish lake environment: Maruwanminami-ike (72.5-65.6 cm, 2,590-2,500 cal BP) and Maruwan-oike (47.2-28.8 cm, 3,190-2,890 cal BP) were characterized by stratified conditions with marine water overlain by freshwater, and a chemocline developed together with an anoxic layer in the bottom of photic zone.

(6) Freshwater lake environment of Maruwanminami-ike (65.6-0 cm, 2,500-1,230 cal BP) was characterized by high biological production by cyanobacteria (e.g. *Leptolyngbya* spp.) and green algae (e.g. *Comarium clepsydra*) with some contribution of diatoms, while that of Maruwan-oike (28.8-0 cm, 2,890-2,240 cal BP) was very low biological production.

(7) The transition ages ranged from 970 to 9,290 yr BP with an average of 3,660±1,520 yr BP (standard deviation) suggesting that the major warm periods in the Soya Coast region are the middle Holocene.

(8) Glacio-isostatic uplift rates of raised basins and isolated basins in the Soya Coast region ranged from 0.19 to 4.40 mm/yr with an average of 2.0±0.92 (standard deviation) mm/yr which is similar to East Antarctica.

(9) Glacio-isostatic uplift rates of raised beaches were correlated with altitudes with a correlation coefficient of $r^2 = 0.724$. Increasing crustal uplift rates with altitudes reflect continuous crustal uplifts in the Soya Coast region.

Abbreviations

East Antarctic Ice Sheet, EAIS; Last Glacial Maximum, LGM; middle Holocene Hypsithermal, MHH; relative sea level, RSL; Lützow-Holm Bay, LHB; modified Circumpolar Deep Water, mCDW; Coastal marine environment, CME; Freshwater lake environment, FLE; brackish lake environment, BLE; total carbon, TC; total organic carbon, TOC; total nitrogen, total inorganic carbon, TIC; total nitrogen, TN; total sulfur, TS; accelerator mass spectrometry, AMS; elemental analyzer/isotope ratio mass spectrometry, EA/IRMS; Vienna Pee Dee Belemnite, VPDB; high-performance liquid chromatography, HPLC; denaturing gradient gel electrophoresis with 16S ribosomal RNA gene analysis, DGGE-16S rRNA; Japanese Antarctic Research Expedition, JARE.

Declarations

Availability of data and material

The datasets supporting the conclusions of this article are included within the article and its additional files.

Supplementary Information

The online version contains supplementary material available at https//doi.org/xxxxxxxxx

Additional files: Tables S1-S8 CNS elements, hydrocarbons, fatty acids, sterols, and chlorophyl compounds and carotenoids tables of the MwS4C-1 sediment core from Lake Maruwanminami-ike as well as CNS elements, $\delta^{13}C$(‰) and $\delta^{15}N$(‰), and chlorophyll compounds and carotenoids tables in the Mw4C-01 sediment core from Lake Maruwan-oike.

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Authors' contributions

GIM, KS and SI proposed the topics and designed the study framework. KS and SI collected the Rundvågshetta lake samples (MwS4C-01 and Mw4C-01), KS performed sedimentary structures and soft X-ray photography analyses, EH, KI and GIM performed CNS elements, hydrocarbons, fatty acids and sterols analyses, WT, EH, KI and TN performed AMS dating, YTani, EH, KT and GIM performed chlorophyll compounds and carotenoids analyses, KI and TY performed $\delta^{13}C$, $\delta^{15}N$ analyses, IK and KK performed the diatom analyses, SO performed microalgae and cyanobacteria analyses, and they interpreted the results. YTakano assessed the geochemical data with the reference sediment core samples of the Rundvågshetta lakes (Ms5S and Mw5S). GIM organized and wrote the present report with contributions from other co-authors. All authors edited and approved the final manuscript.

Authors' information

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Endnotes

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Tables

Tables 1-7 are available in the Supplementary Files section.

Figures

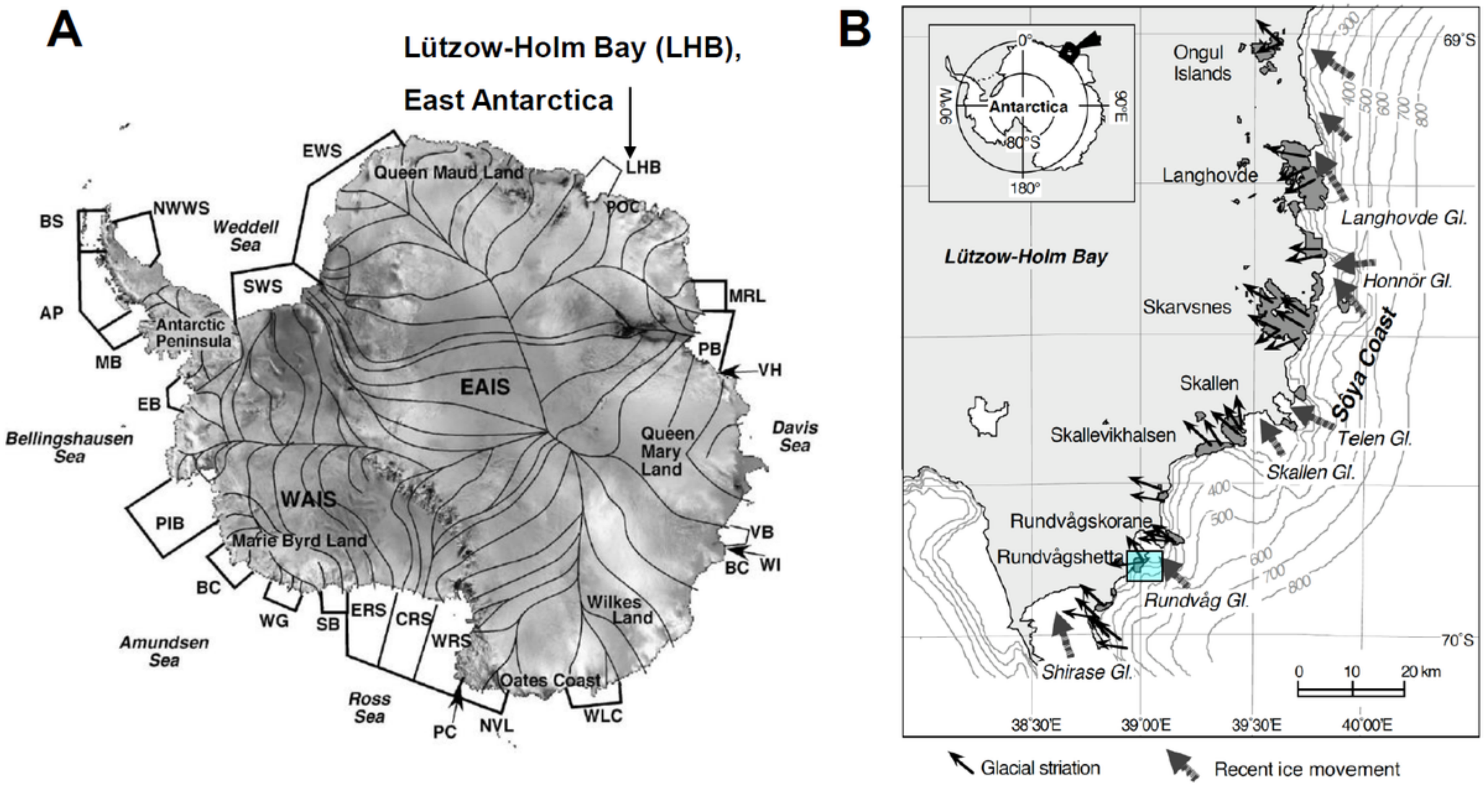

Figure 1

Drainage map of the Antarctic Ice Sheet and lakes Maruwanminami-ike and Maruwan-oike of Rundvågshetta in the Soya Coast of East Antarctica (modified from Takano et al. 2015). **A:** Drainage map of the Antarctic Ice Sheet showing areas where marine and geological surveys are being conducted to record the extent of the Last Glacial Maximum (LGM, Anderson et al. 2002). **B:** Detail of the Soya Coast and Lützow-Holm Bay showing the locations of ice-covered (white), ice-free (shaded) and marine (grey) areas. Arrows show the flow directions of the present outlet glaciers (after Sawagaki, Hirakawa 1997). Topography at Rundvågshetta, the locations of Lakes Maruwan-oike and Maruwanminami-ike are shown in Fig. 2. NWWS, northwestern Weddell Sea; BS, Bransfield Strait; AP, Antarctic Peninsula; MB, Marguerite Bay; EB, Eltanin Bay; PIB, Pine Island Bay; BC, Bakutis Coast; WG, Wrigley Gulf; SB, Sulzberger Bay; WRS, Western Ross Sea; CRS, Central Ross Sea; ERS, Eastern Ross Sea; NVL, Northern Victoria Land; WLC, Wilkes Land Coast; PC, Pennell Coast; BC, Budd Coast; WI, Windmill Islands; PB, Petersen Bank; VB, Vincennes Bay; VH, Vestfold Hills; PB, Prydz Bay; MRL, Mac. Robertson Land; POC, Prince Olav Coast; LHB, Lützow-Holm Bay; EWS, eastern Weddell Sea; SWS, southwestern Weddell Sea (modified from Anderson et al. 2002).

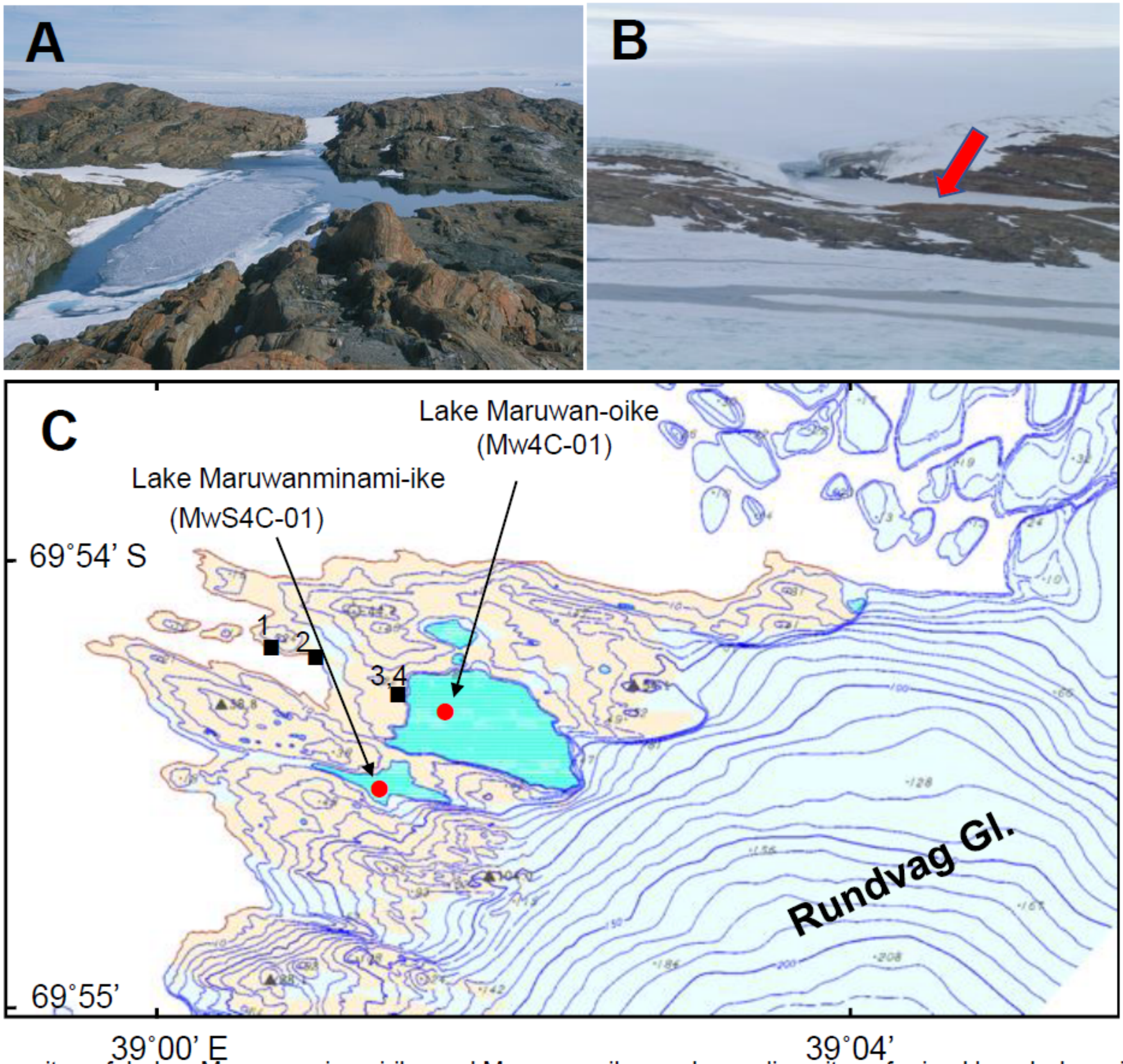

Fig. 2 Coring sites of Lakes Maruwanminami-ike and Maruwan-oike, and sampling sites of raised beach deposits.
A: Lakes Maruwanminami-ike viewed from the east northeast side of the lake (69o54'37"S, 39o02'17"E , Photo by Imura, S.).
B: Lake Maruwan-oike viewed from the Lützow-Holm Bay (69o54'26"S, 39o02'41"E, Photo by Seto, K.).
C: MwS4C-01 coring site (● 69° 54'36.9"S, 39° 2'16.6"E) . Mw4C-01 coring site (● 69° 54'25.7"S, 39° 2'41.3"E).
Raised beach deposits (■1, c940112-3;■2, M940112-4;■3, N940114-3A;■4, d940114-3B (Hirakawa, Sawagaki 1998).

Figure 2

See image above for figure legend.

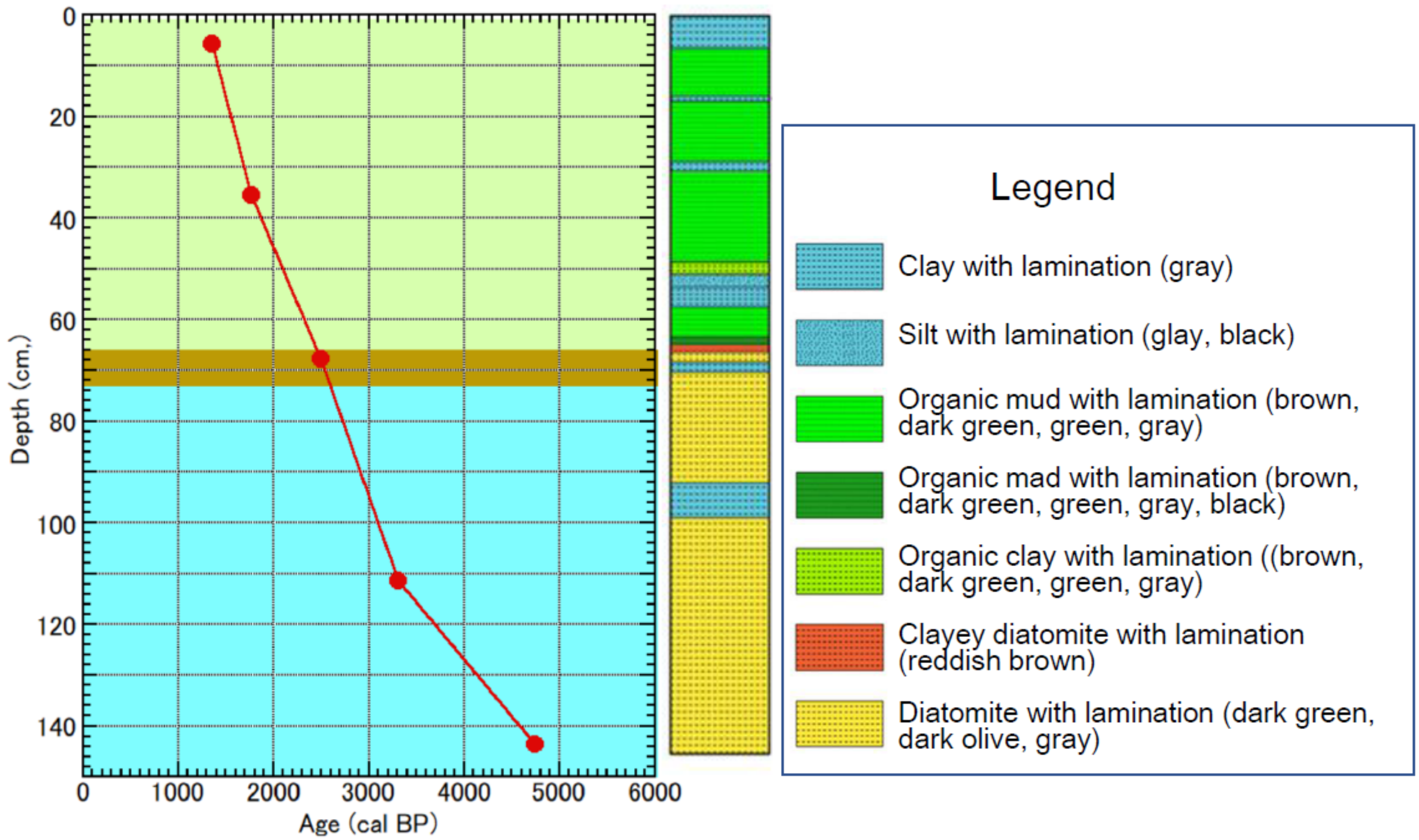

Figure 3

Sediment core structure, calibrated age of MwS4C-01 sediment core from Lake Maruwanminami-ike. Light blue: Coastal marine environment. Light brown: Brackish lake environment. Light green: Lacustrine lake environment.

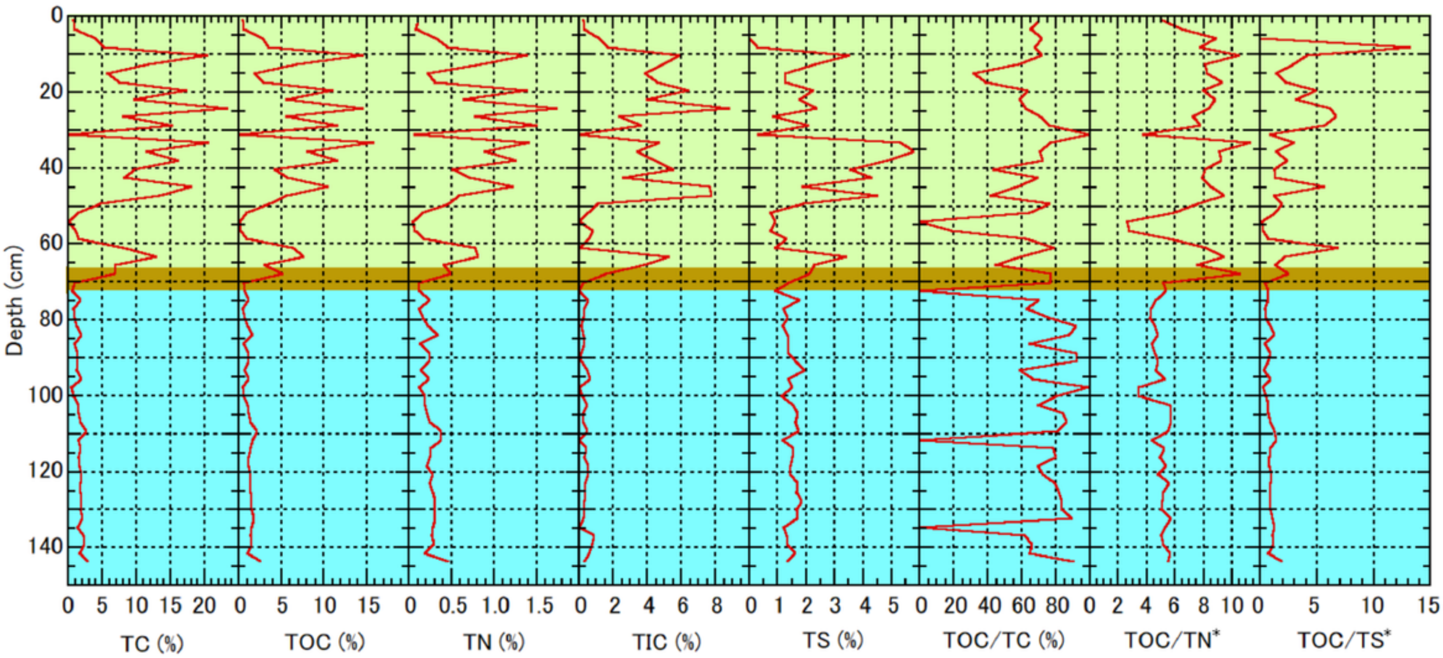

Figure 4

TC, TOC, TN, TIC and TS concentrations, and TOC/TC, TOC/TN and TOC/TS weight ratios of the MwS4C-01 sediment core from Lake Maruwanminami-ike. Light blue: Coastal marine environment. Light blue: Coastal marine environment. Light brown: Brackish lake environment. Light green: Lacustrine lake environment. *Weight ratio.

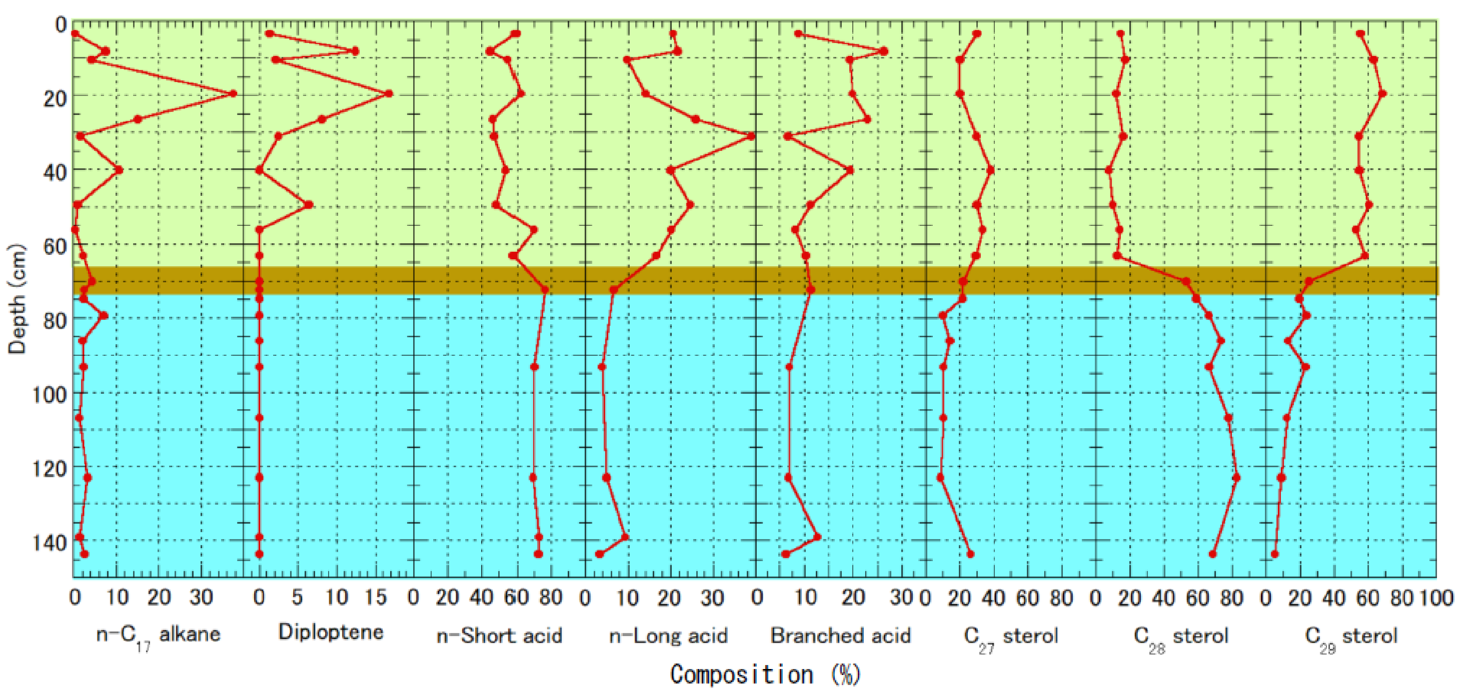

Figure 5

Selected hydrocarbons, fatty acids and sterols in the MwS4C-01 sediment core from Lake Maruwanminami-ike. Composition of n-C17 alkane and diploptene, n-short alkanoic (C12-C19), n-long alkanoic C20-C36) and branched (iso and anteiso C12-C18) acids, and C27-C29 sterols was calculated from hydrocarbon, fatty acids and sterols, respectively. Light blue: Coastal marine environment. Light brown: Brackish lake environment. Light green: Lacustrine lake environment.

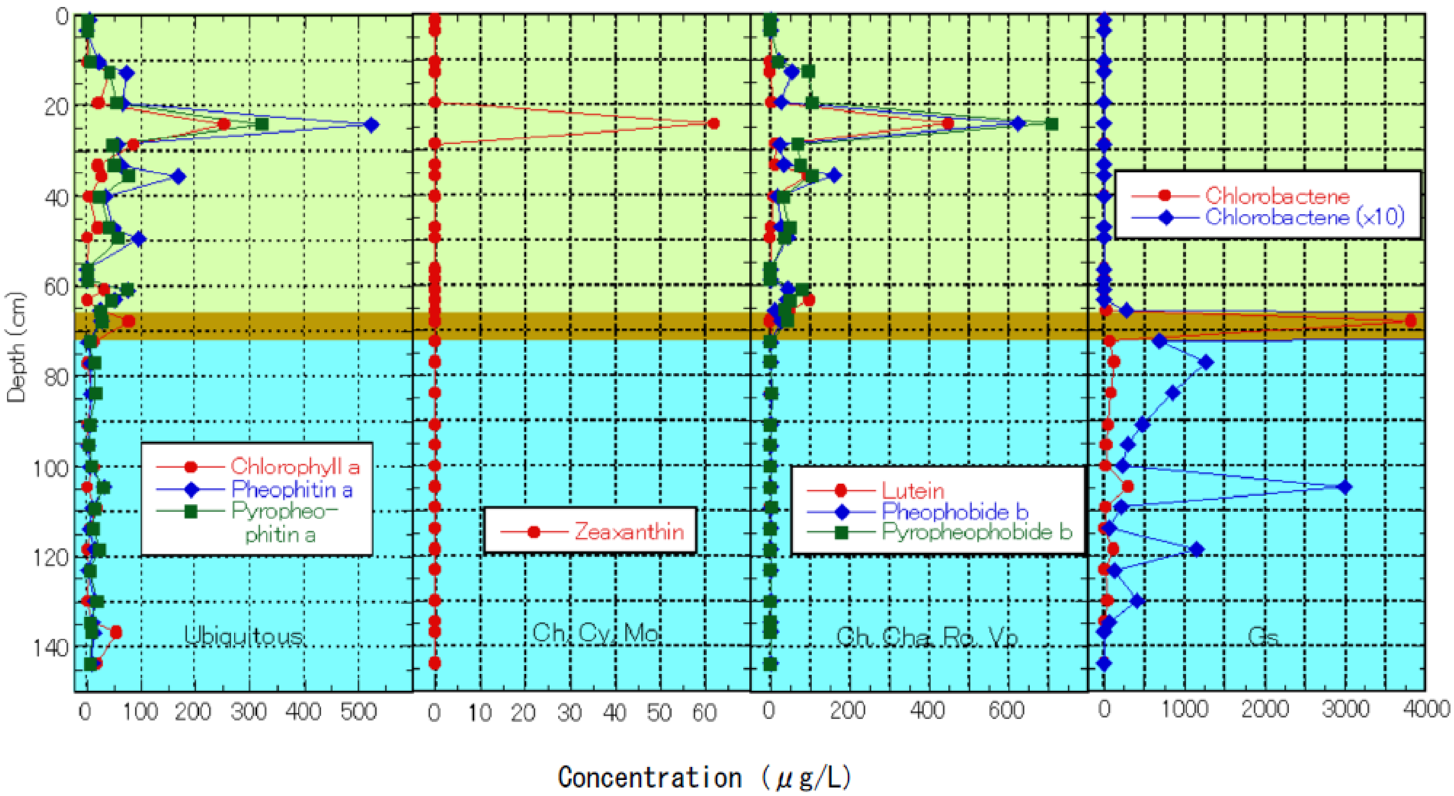

Figure 6

Chlorophyll compounds and carotenoids found in the MwS4C-01 sediment core from Lake Maruwanminami-ike Ch, Chlorophyceae; Cha, Charophyceae; Cy, Cyanophyceae; Gs, Green sulfur bacteria; Mo, Mosses; Ro, Rhodophyceae; Vp, Vascular plants. Chlorophyll a, pheophythin a and pyrophyophytin a: ubiquitous (Verleyen et al. 2004; Tani et al. 2009). Zeaxanthin: Chlorophyceae, Cyanophyceae and mosses (Verleyen et al. 2004; Hodgson et al. 2006). Lutein: Charophyceae, Chlorophyceae, Rhodophyceae, and vascular plants (Verleyen et al. 2004; Tani et al. 2009). Pheophobide b, pyropheophorbide b: Similar to lutein. Chlorobactene: Green sulfur bacteria (Pfennig 1967; Borrego and Garcia-Gil. 1994; Squier et al. 2002). Light blue: CME. Light brown: BLE. Light green: LLE.

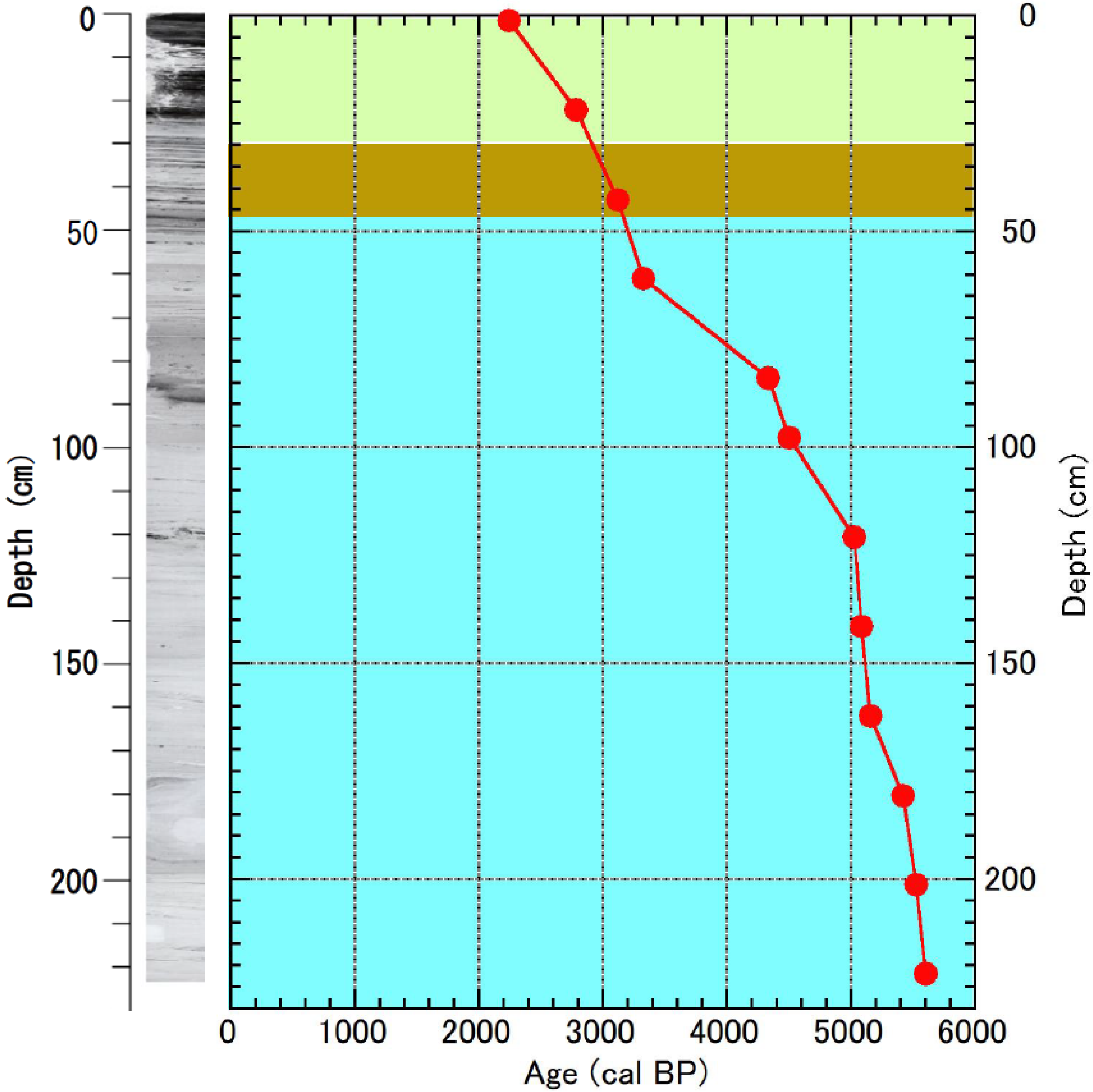

Figure 7

Soft X-ray photograph, calibrated age (cal BP) of Mw4C-01 sediment core from Lake Maruwan-oike. Light blue: Coastal marine environment. Light brown: Brackish lake environment. Light green: Lacustrine lake environment.

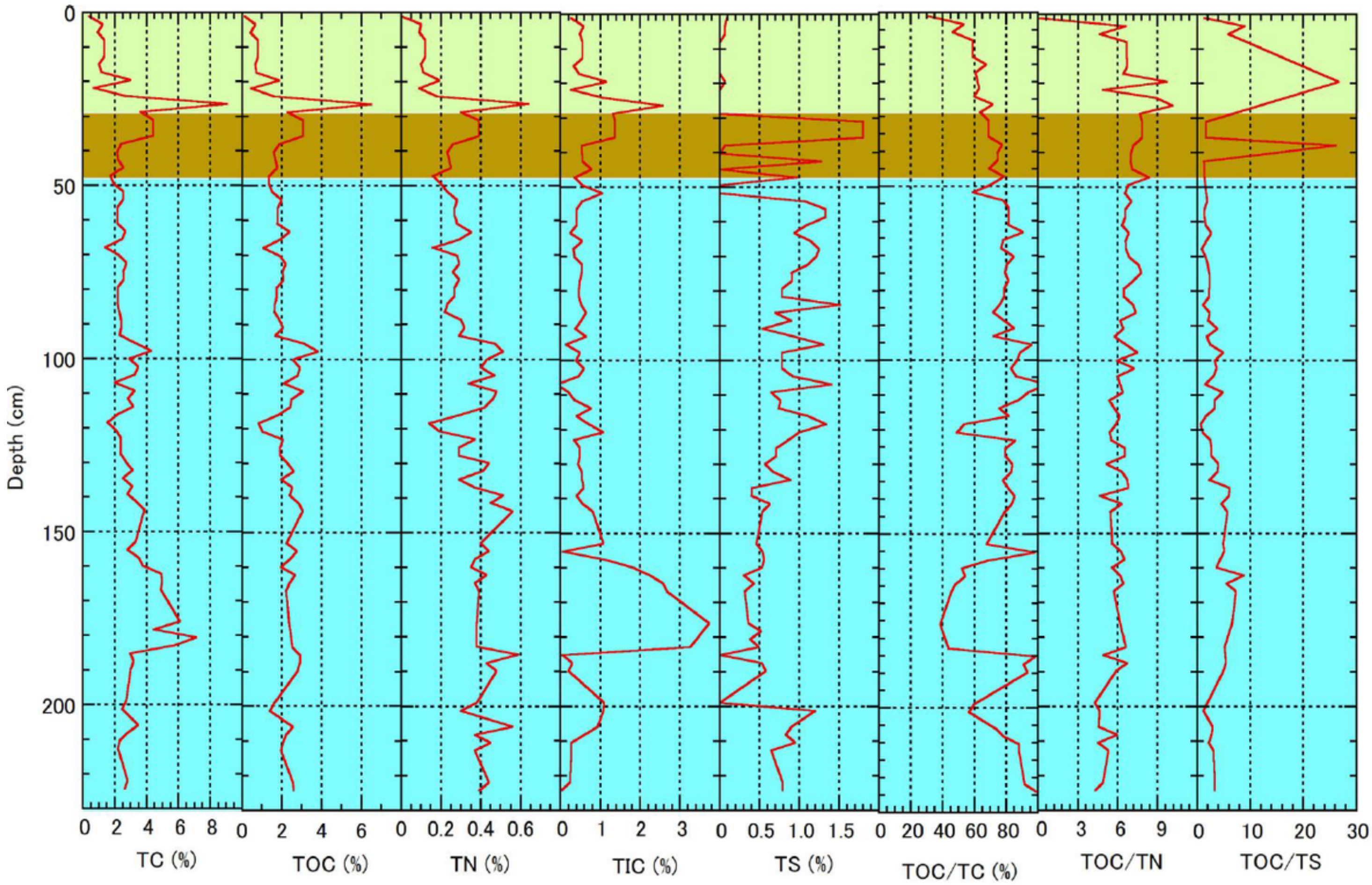

Figure 8

TC, TOC, TN, TIC and TS contents, and TOC/TC, TOC/TN and TOC/TS weight ratios in Mw4C-01 sediment core from Lake Maruwan-oike. Light blue: Coastal marine environment. Light brown: Brackish lake environment. Light green: Lacustrine lake environment.

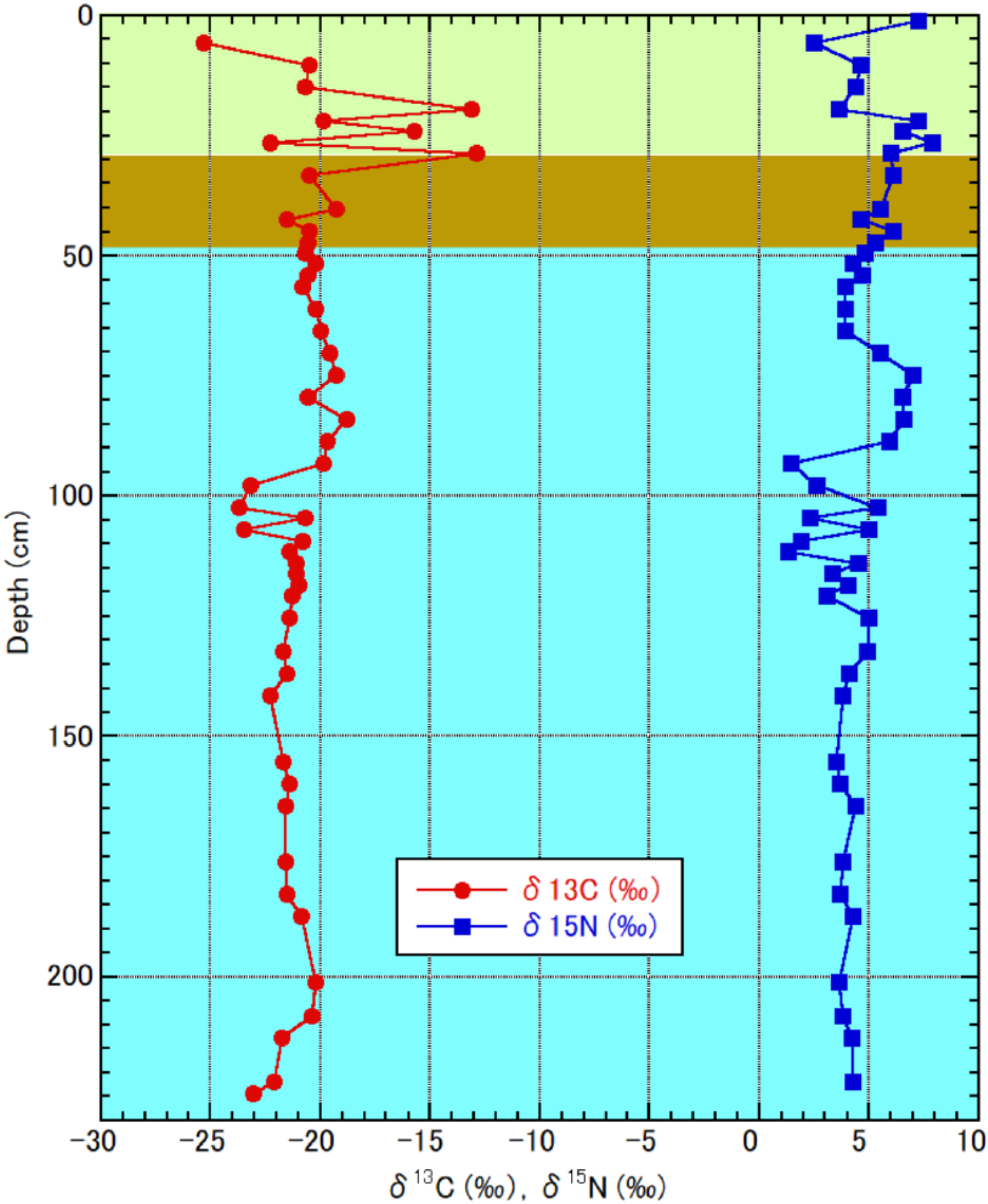

Figure 9

Stable isotope ratios of δ13C and δ15N in Lake Maruwan-oike sediment core (Mw4C-01). Light blue: Coastal marine environment. Light brown: Backish lake environment. Light green: Lacustrine lake environment.

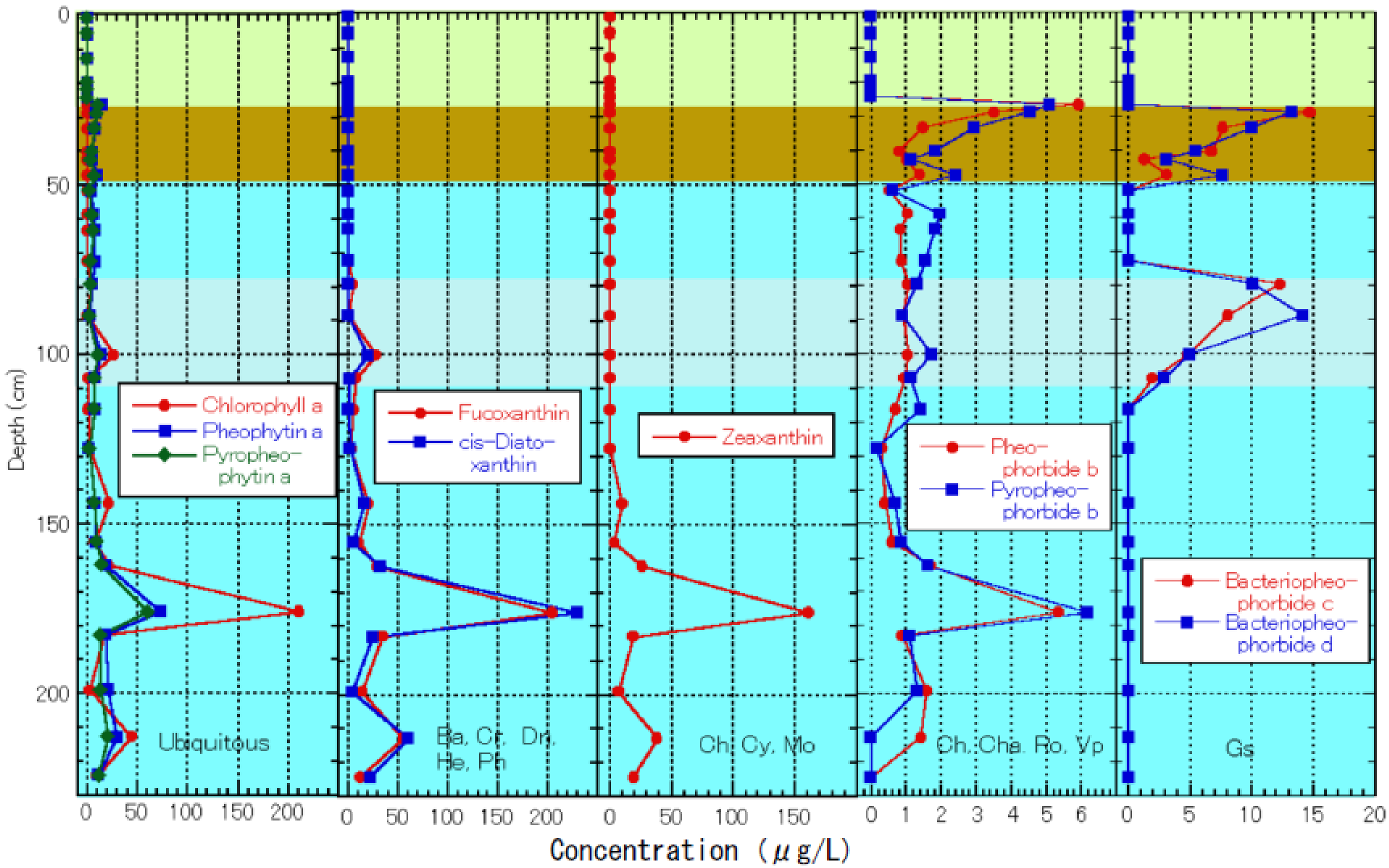

Figure 10

Chlorophyl compounds and carotenoids found in the Mw4C-01 sediment core from Lake Maruwan-oike. Ba, Bacillariophyceae; Dn, Dinopyceae; He, Heptophyceae; Ph, Phaeophyceae; Fucoxanthin and cis-diatoxanthin: Bacillariophyceae, Chrysophyceae, Dinophyceae, Heptophyceae and Phaeophyceae (Verleyen et al. 2004). Bacteriopheophorbide c and bacteriopheophorbide d: Green sulfur bacteria (Pfennig 1967; Borrego and Garcia-Gil. 1994; Squier et al. 2002). Other abbreviations and relationships of pigments and organisms are shown in explanations of Fig. 7. Light blue: CME. Light gray: CME with anoxic photic zone. Light brown: BLE. Light green: LLE.

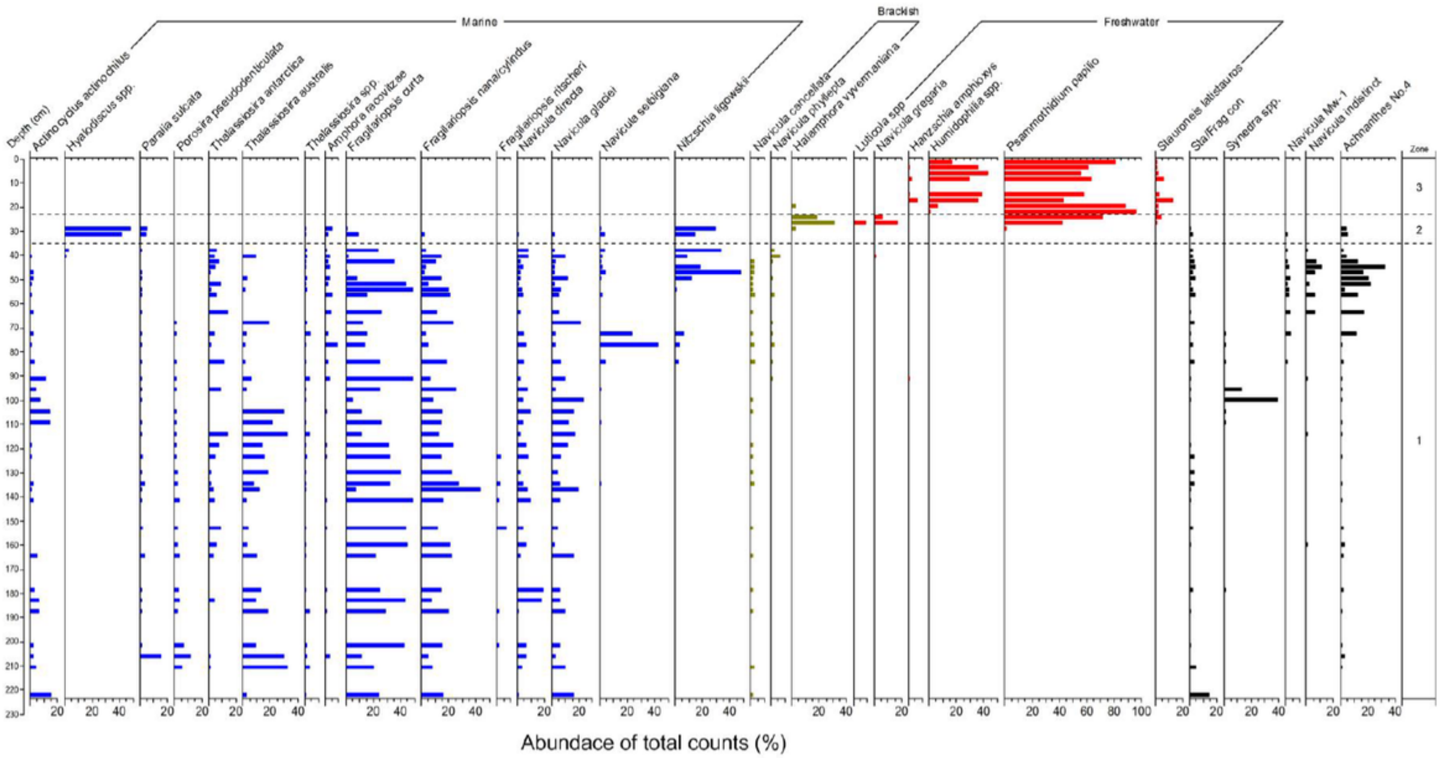

Figure 11

Relative percentage diagram of diatom assemblage in Mw4C-01 sediment core from Lake Maruwan-oike (modified from Kang, 2018).

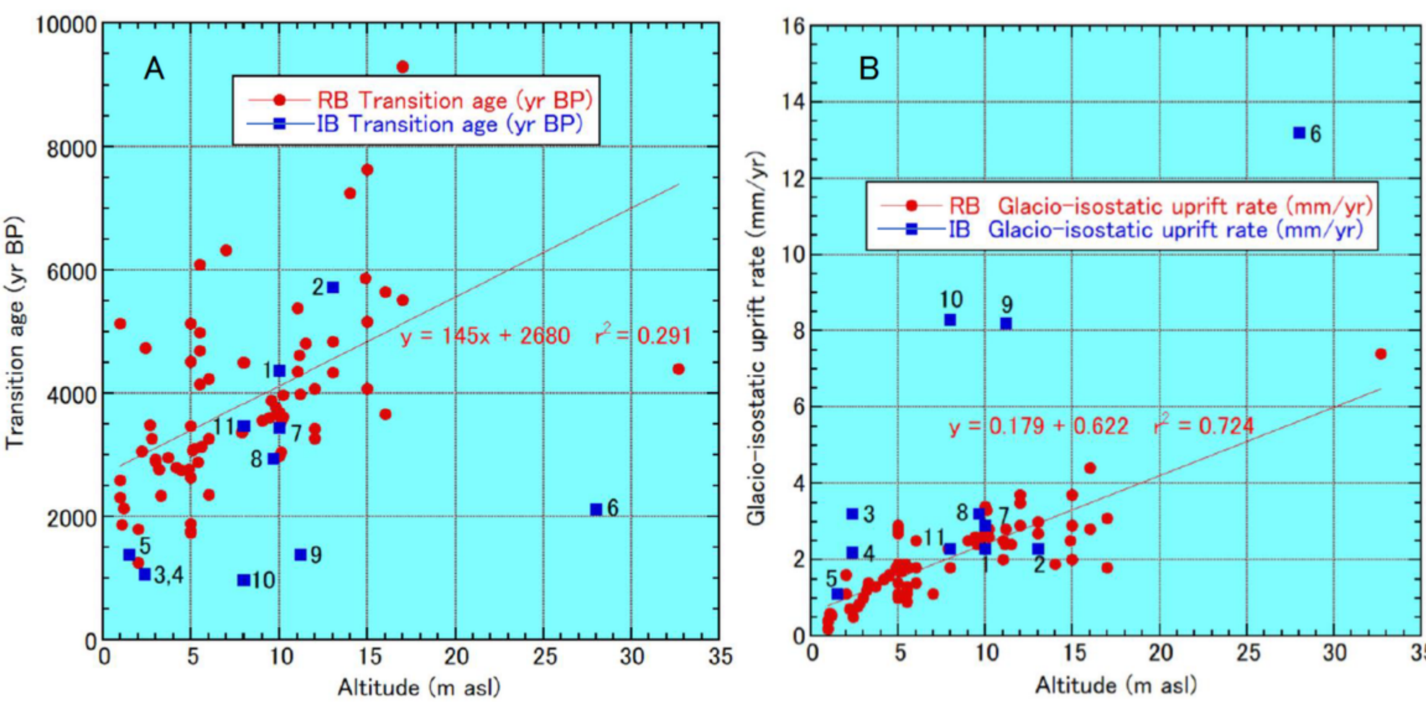

Figure 12

Correlations between altitudes, glacio-isostatic uplift rates and transition ages in raised beaches (RB) and isolation basins (IB) from the Soya Coast region . 1, L. Yumiike; 2, L. Oike; 3, L. Oyako-ike (T); 4, L. Oyako-ike (M); 5, L. Mago-ike; 6, L. Kobachi-ike; 7, L. Skallen-oike (M); 8, L. Skallen-oike (T); 9, L. Maruwanminami-ke; 10, L. Maruwan-oike (M); 11, L. Maruwan-oike (T).

Supplementary Files

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