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ПАЛЕОГЕОГРАФИЯ ПОЗДНЕЛЕДНИКОВЬЯ И ГОЛОЦЕНА

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THE MIDDLE–LATE HOLOCENE CLIMATIC FLUCTUATIONS RECORDED IN SEDIMENTARY SEQUENCE OF LAKE GEOGRAPHENSEE, FILDES PENINSULA (KING GEORGE ISLAND, WEST ANTARCTICA)[1]

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The article focuses on the paleoclimatic reconstruction of Holocene environmental changes. To address this issue, a study of the bottom sediments of Lake Geographensee, located on the Fildes Peninsula, King George Island, West Antarctica, was conducted. The lake, located above the maximum Holocene marine transgression limit, preserves an undisturbed sediment record spanning the last 8500 cal. yr BP. The results of lithological, loss-on-ignition, grain size, diatom, and geochemical analyses, along with statistical data processing and radiocarbon chronology of the bottom sediments, are presented. The study allows to identify significant and minor stages of climate change. A prominent warming occurred between ca. 4800–3400 cal. yr BP. Minor warming intervals were identified at ca. 8500–8000 cal. yr BP, ca. 5600–5300 cal. yr BP, ca. 5130–4800 cal. yr BP, ca. 3400–2400 cal. yr BP, and ca. 1200–800 cal. yr BP. A notable cooling stage transpired at ca. 7500–5600 cal. yr BP, with a peak cold period around 7300–7000 cal. yr BP, and possibly at ca. 1800–1200 cal. yr BP. Minor relative cooling phases took place during next periods: ca. 8000–7500 cal. yr BP, ca. 5300–5130 cal. yr BP, and ca. 2400–1800 cal. yr BP. Additionally, short-term relative cooling and warming are suggested to have occurred during the period ca. 800–600 cal. yr BP. Taking into account the absence of suitable glaciers for obtaining the ice core for paleoclimatic records in the considered maritime Antarctic region, this paleolimnological study provides a foundation for broader understanding of the Holocene climate change in the West Antarctica.

Keywords: Holocene climate, lake sediments, lithology, radiocarbon chronology, magnetic susceptibility, geochemistry, diatoms

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1. INTRODUCTION

The northern Antarctic Peninsula with nearby islands (West Antarctica) demonstrate one of the most dynamic glaciers reduction examples on Earth at the turn of the XX–XXI centuries (Vaughan et al., 2003; Steig et al., 2009; Rückamp et al., 2011; Bromwich et al., 2012). Repeated fluctuations in the size of glaciers occurred here in the Holocene (Verkulich, 2022; Barion et al., 2023), confirming the high sensitivity of local glaciation to changes in climate and sea level. Understanding the causes and mechanisms of these changes is necessary for the predictive modeling of the future changes. This is especially important considering the undeniable significance of the West Antarctic glaciation in balancing the global atmosphere-ocean-glacial system (Bentley, 1999; Hodgson et al., 2009, Lüning et al., 2019).

In this context, lake deposits in periglacial territories represent one of the best natural archives of continuous records of climate and environmental changes (Hodgson et al., 2004; Subetto, 2009). On the Fildes Peninsula (King George Island), the largest ice-free area on South Shetland Islands (fig. 1), lake sediment studies provided information on relative sea level (RSL) changes, the chronology of deglaciation and sedimentation conditions in lakes during the Holocene (Mäusbacher et al., 1989; Matthies et al., 1990; Schmidt et al., 1990; Martinez- Macchiavello et al., 1996; Tatur et al., 2004; Watcham et al., 2011; Verkulich et al., 2012; Roberts et al., 2017; Barion et al., 2023,). However, these studies did not give a clear comprehension of the post-glacial climatic conditions

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in the region due to gaps in sedimentation record. Some of the studied lakes are located at elevations below 20 m a.s.l. (above sea level), and their basins were filled with seawater during transgressions up to the middle–late Holocene (Polishchuk et al., 2017). Other lakes due to the late time of formation or the peculiarities of their catchment contain short-term or incomplete paleoclimatic information. The only exceptions were the deposits of the Lakes Jurasee and Mondsee (fig. 1) located above 20 m a.s.l. and existing since the early Holocene (Mäusbacher et al., 1989; Schmidt et al., 1990). However, the range and detail of the methods used in these studies allowed us to get only a general idea of the main sedimentation stages. To eliminate gaps in knowledge about the climatic component of Holocene environmental changes in the Fildes Peninsula area we present and interpret new data from detailed analytical studies of sediments sampled in 2019 from Lake Geographensee, located near Lake Jurasee (fig. 1). The data interpretations are compared with paleolimnological information collected in the Fildes Peninsula earlier in order to confirm and evaluate the identified climatic signals.

1.1. Area and object of study

The Fildes Peninsula is located in the southwestern part of King George Island, West Antarctica. Most of the peninsula with an area approximately 30 km² is ice free, with an exception of the Bellingshausen Ice Cap located in its northeastern part (fig. 1). The peninsula climate is marine. Seasonal temperature variations during the period of 1968–2020 are low with the average air temperature of the December–March period 0.94 °C, April–November period –3.89 °C. Average annual humidity reaches 83% and annual precipitation about 700 mm (more than 200 mm in summer, often in the form of rain), with prevailing NW winds with average monthly speeds of up to 8 m/sec (Simonov, 1975; Mavlyudov, 2022). The main elements of the peninsula landscape are structural denudation massifs with an elevation of 100–150 m a.s.l. located in the center and in the south, composed mainly by andesites, basalts and various tuffs, an ancient abrasive surface at altitudes of 35–50 m a.s.l., and numerous valleys of mainly sub latitudinal direction, covered with glacial, marine, alluvial, and colluvial-deluvial deposits.

Lake Geographensee with an area of about 0.01 km^2 (62°13′00.0″ S, 59°01′00.0″ W, 40 m a.s.l.) is located next to Lake Jurasee (47 m a.s.l.) in the flat, wide and short valley that crosses the southern tip of the peninsula from northwest to southeast (fig. 2). The elevation of the valley floor ranges from 40 m to 50 m a.s.l., being over all higher around Lake Jurasee than around Lake Geographensee. The valley floor between Lakes Geographensee and Jurasee is flat and elevated by 2–3 m above 50 m a.s.l. Along the northern and southern boundaries of this section of the valley there are short dry stream beds that may have previously connected the lakes if the water level in Lake Jurasee rose to a height of 50 m a.s.l. Lake Geographensee catchment of about 0.2 km^2 includes the valley floor and gently descending slopes, that stretch to the northeast and southwest from the lake at the heights of about 65 m a.s.l. into steep slopes of bedrock outcrops. Northwest of the lake the valley bottom descends to the seashore, at first relatively steeply, and then becomes gentle in the coastal part. Currently, the lake's water outflows from its northwestern part during periods of maximum melting in the summer along the bottom of a narrow channel cut into the valley floor. Judging by the depth of this channel, the lake level in the past could have been several meters higher. The floor of the valley and the lake's catchment slopes are covered mainly with fine-grained sediments (silt, loam) with mixture of gravel and rubble. Rare vegetation in the catchment area is represented by patches of mosses mostly concentrated in small moist relief irregularities and in the temporary stream beds through which the melted waters from small snowfields flow.

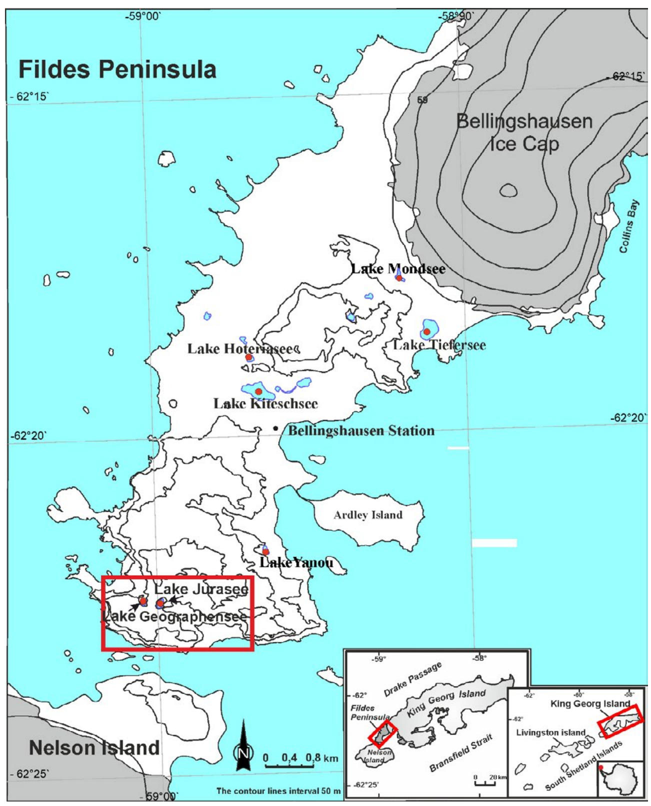

Fig. 1. Map of the research area on the Fileds Peninsula, King Georg Island, West Antarctica with locations of geographic objects mentioned in the text.

Рис. 1. Карта района исследований на полуострове Файлдс, остров Кинг Джордж, Западная Антарктика, с местоположением географических объектов, упоминаемых в тексте.

Measurements in 2019 showed that Lake Geographensee has a mean depth of 3.5 m, and the maximum depth of 4 m. Its hydrological characteristics should be similar to those determined during the study of other freshwater lakes of the peninsula, similar in size and located at the same altitude. Water balance is dominated by precipitation (snow and rain). Release from ice cover occurs in January–February (Lake Geographensee is the last to release). The waters of such lakes are classified as the chloride class of the sodium group (Alyokin, 1970), have the pH value from 7 to 8.3, with 89% average oxygen content in the surface layer, and are mixed due to wind in the summer ice-free period (Skorospekhova et al., 2016; Shevnina, Kourzeneva, 2017). Lake Geographensee water chemistry is most likely characterized by the same low values of PO_4 (<0.2 mcg/L) and NO_2+NO_3 (2.2 mcg/L), and low SiO_2 content (937.0 mcg/L) as Lake Jurasee (Skorospekhova et al., 2016).

2. MATERIALS AND METHODS

Five sediment cores were taken from the deepest part of Lake Geographensee (62°13'25.8"S, 59°0'17.5" W) from the water depth of 3.84 m using Russian corer (Subetto, 2009). At the time of core recovery, the lake surface was covered with 0.8 m of ice. One meter long and 5 cm in diameter sediment cores were retrieved with a 10–20 cm overlap. The overlapping segments of sediment cores were compared visually by defining distinct marker-layers and other prominent features of lithology, using photoscan data and magnetic susceptibility measurements. As a result, the five cores provided 4.24 m long continuous sedimentary sequence, with an exception of a few top centimeters that were lost during coring due to high water content of the upper sediment layer. The sequence underwent physical, geochemical and biological analyses to obtain information about changes in sedimentation conditions in the lake.

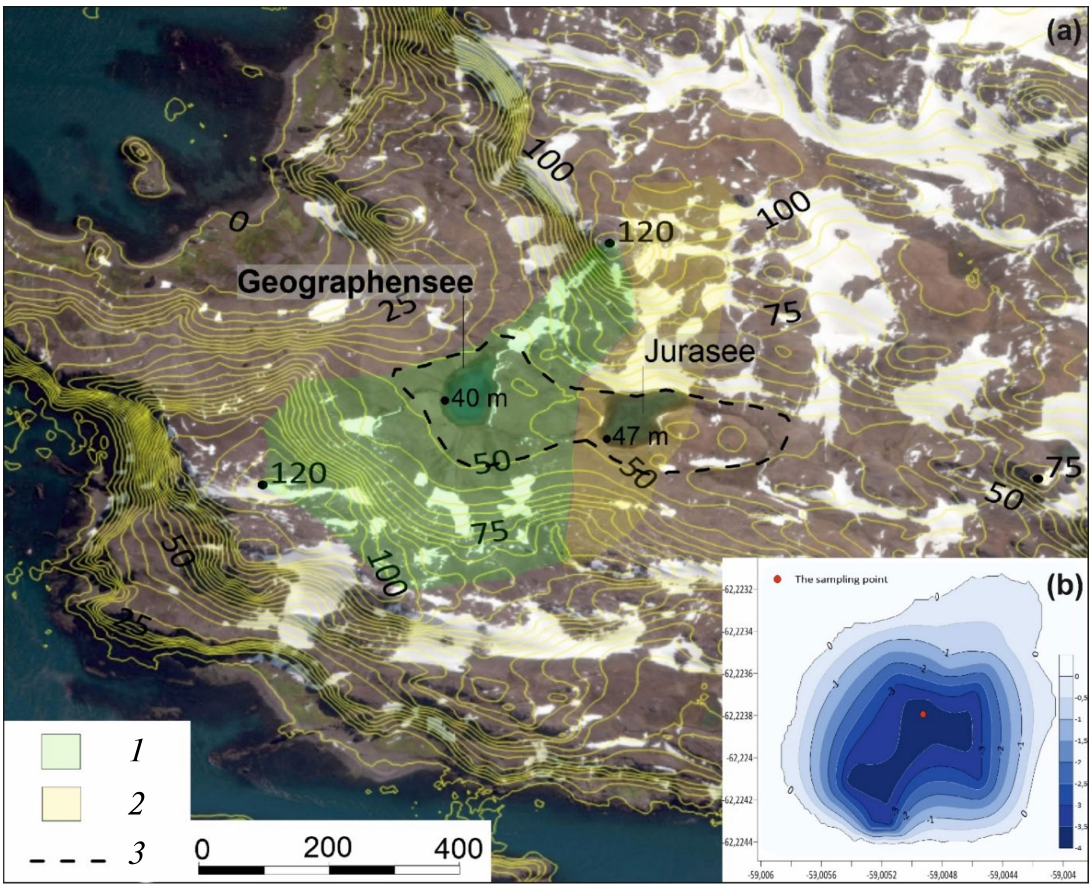

Fig. 2. A satellite image of the research area with contour lines drawn at 5 m contour interval (a) and bathymetry of Lake Geographensee and the sampling point (b).
1 – The catchment area of Lake Geographensee; *2* – The catchment area of Lake Jurasee; *3* – The proposed contours of the paleobasin.

Рис. 2. Спутниковый снимок района исследований с обозначенными изогипсами (интервал – 5 м, подписи указаны через 25 м) (a) и батиметрическая карта озера Географов и точка пробоотбора (b).
1 – площадь водосборного бассейна озера Географов; *2* – площадь водосборного бассейна озера Юра; *3* – предполагаемые контуры палеобассейна.

Main lithological distinctions in the sediment cores were determined by color, layers characteristics, organic macrofossils presence, sediment texture, and were refined during further analyses.

Multisensory scanning of cores using the automated Geotek MSCL-XYZ system was performed at the Laboratory of Paleooceanology of the P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences (Moscow, Russia). Analysis included photo scanning, measurement of magnetic susceptibility and determination of elemental composition (Croudace, Rothwell, 2015). Photo scanning was performed with polarizing filters on the camera lens and illuminator lamps, with a resolution of 400 and 200 lines per cm; 11 high-quality photos of sedimentary cores were obtained. Magnetic susceptibility in SI 10–5 units was measured in 5 mm increments using the Bartington MS3 system and the Bartington MS2E point sensor. The elemental composition of sediment was determined using a Geotek X-ray fluorescence spectrometer (Rh anode) with a helium cell, with a step of 2–10 mm and the size of a single analysis area ranging from 15×1 mm to 15×10 mm. The following elements were identified: Na, Mg, Al, Si, P, S, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co (all – at a voltage of 10 kV on the X-ray tube), and Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Tc (all – at a voltage of 40 kV).

Principal Component Analysis (PCA) and correlation were applied to identify patterns of changes in the concentration of certain elements with depth using StatSoft Statistica 11.0 (Dell Corporation, Austin, Texas, USA).

Elements whose Pearson correlation coefficients were positive and exceeded 0.73 were sorted into groups associated with various mineral fractions and reflecting sedimentation features. PCA was used to study the relationships between the values of elementary variables for the entire sedimentary sequence (Minyuk et al., 2014).

The organic, carbonate and mineral components sediment ratio was analyzed in 2 cm increments (samples with a volume of ~ 1 cm^3 were used) by the method of losses-on-ignition (LOI). Samples were ignited in the muffle furnace at 550 °C (for 4 hours) to estimate the organic matter (OM) burnout and at 950 °C (for 2 hours) for carbonates burnout (Dean, 1974).

The grain size analysis of every 2 cm of the sedimentary sequence was performed on a laser microparticle analyzer LASKA (Russia) by laser diffraction. In the preparation for grain size analysis the samples were treated with 30% hydrogen peroxide (H_2O_2) in order to remove the organic component and then heated to ~ 80 °C in a water bath in accordance with (Vaasma, 2008). For each sample, 3 measurements were carried out to determine the percentage of fractions from 0.5 to 0.001 mm and the average diameter of the particles. Later, the average values were calculated.

Diatom analysis was performed for samples at 3–5 cm intervals following the standard procedures (Jousé et al., 1969). To clean the diatom valves from the organic matter, 0.5 g of sediment was heated with H_2O_2 (30%). Centrifugation of the sediment to separate the fraction was carried out at 1500 rpm. Sediment was then washed in distilled water to remove H_2O_2 and silt and clay particles. A small sample (0.08 ml of suspension) was taken from a 100 ml suspension using a graduated pipette and mounted onto a permanent slide. The samples were processed for light microscopy. Genera and species identification were based on (Van de Vijver et al., 2002; Sterken et al., 2015, and others). Three hundred diatom valves per sample were counted at × 1000 where possible. Diatom diagrams were constructed using C2 software (Juggins, 2007).

Five bulk sediment samples and one sample of organic material (mosses) taken from different lithological units of sediment cores were submitted to DirectAMS Radiocarbon Lab (Bothell, Washington, USA) and Laboratorium Datowań (Kracow, Poland) for Accelerator Mass Spectrometry (AMS) radiocarbon dating. Obtained dates were input into OxCal v. 4.2.4 (Ramsey, Lee, 2013) for calibration using the IntCal 20 calibration curve (Reimer et al., 2020).

3. RESULTS

3.1. Geochronology

The depth-age model of the sedimentary sequence in Lake Geographensee is based on six radiocarbon dates (tab. 1, fig. 3). From ca. 8500 calibrated years ago (cal. yr BP) to ca. 600 cal. yr BP, sediment accumulation proceeded at low rates (minimum was about 0.1 mm/year in the period ca. 7300–5500 cal. yr BP) except for a short time interval ca. 5500–4950 cal. yr BP when the average sedimentation rate has increased to about 4.2 mm/year (by almost 40 times).

3.2. Lithology and physical properties of sediments

Ten lithological units (U10 – U1) in Lake Geographensee sedimentary sequence were identified based on organic macrofossils, color, degree of lamination and texture, as well as by concomitant variations in grain size proportions, organic matter content (OM) and values of magnetic susceptibility (MS) (fig. 4):

U 1 (4.24–4.22 m). Gray laminated mud with ~7% of OM, and ~180 value for MS. The thickness of alternating grayish with grayish beige and black layers is 1–2 mm.

Table 1. List of radiocarbon dates (years BP), calibrated ages (cal. yr BP) and dated material
Таблица 1. Список радиоуглеродных дат (л. н.), калиброванного возраста (кал. л. н.) и датированных материалов

Lab ID	Core ID	Depth from the bottom surface, cm	Dated material	Radiocarbon date	Calibrated age (95.4% probability)	Median age
D-AMS 051934	KDG-13	3.5–4.5	Sediment (bulk)	631±31	553–659	600
MKL-A6238	KDG-13	59–62	Sediment (bulk)	2819±26	2854–2996	2919
D-AMS 050518	KDG-14	111.5–112	Organic	4348±30	4847–5025	4913
D-AMS 050520	KDG-17	352–352.5	Sediment (bulk)	4731±29	5326–5580	5474
D-AMS 050521	KDG-17	376–376.5	Sediment (bulk)	6372±41	7170–7422	7297
D-AMS 051939	KDG-17	421–424	Sediment (bulk)	7714±38	8414–8589	8490

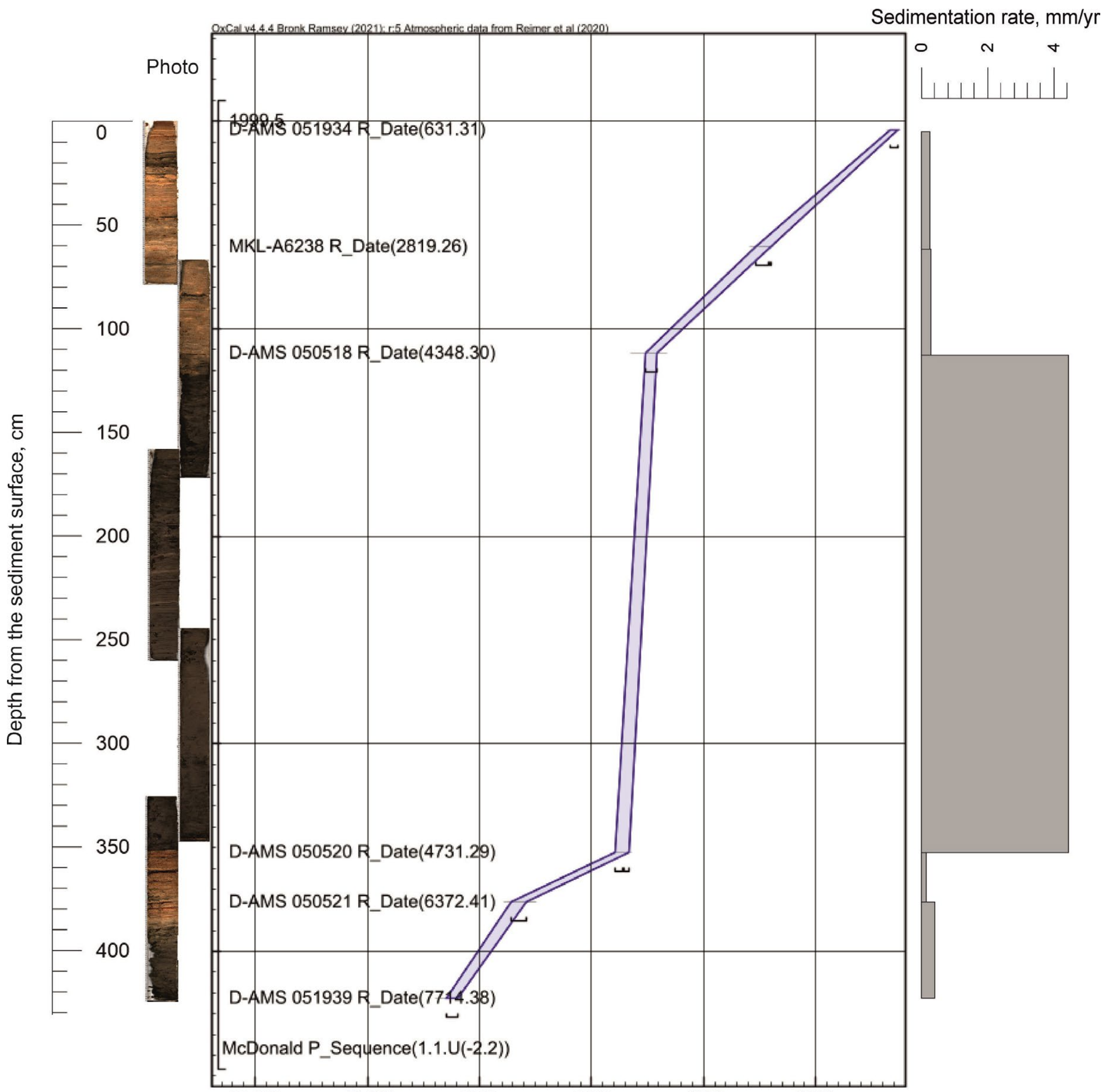

Fig. 3. Age-depth model and sedimentation rate of Lake Geographensee.
Рис. 3. Глубинно-возрастная модель и скорость накопления донных отложений оз. Географов.

U 2 (4.22–4.14 m). Black-gray sandy mud with a decrease in OM (<2%), a content of sand up to 30%, an increase in MS up to ~350.

U 3 (4.14–3.88 m). Dark gray mud with alternating implicit 5 mm thick layers of dark gray and light gray mud from (4.04–3.88 m) to 1–2 mm (4.14–4.10 m), with low OM (2–3%) and a decrease in MS value from about 340 to about 115. The interval 4.04–4.10 m is moist.

U 4 (3.88–3.50 m). The laminated dark gray, beige, bluish mud, with an inclusion of organic macrofossils (mosses), absence of sand fraction, high OM content (5–28%), and low MS values (60–160). The lamination is uneven, the thickness of mud layers is from 2 mm to 18 mm, a dark brown layer with mosses lies at the depth of 3.60–3.62 m.

U 5 (3.50–2.78 m). Dark gray-beige homogeneous sandy mud with low OM (<2%), with sharply incresing value MS that reached more than 400, with an increase up to 11–16% in the content of the sand fraction in several intervals.

U 6 (2.78–2.58 m). Dark gray-beige homogeneous mud with low OM (<2%), sharp fluctuation of MS values between 260 and 420, and up to about 5% of sand content.

U 7 (2.58–2.05 m). Indistinctly layered (layers are from 2 mm to 10 mm thick) gray and dark beige mud with less than 2% of OM, with several MS value fluctuations between 290 and 440, intermittent low (<5%) content of sand, except for the interval 2.20–2.18 m (7%.).

U 8 (2.05–1.46 m). Gray-beige mud with black, sand–rich (up to 12%) layers 10–50 mm (2.05–1.66 m) and 5–10 mm (1.66–1.46 m) thick, with low OM (<2%), and with numerous fluctuations in MS values between 250 and 440.

U 9 (1.46–1.16 m). Dark beige homogeneous sandy mud with an OM of 1.0–1.8%, predominantly high MS values (240–440), and an increased content of sand fraction with a maximum value of 49%.

U 10 (1.16–0.00 m). The laminated olive, dark gray, yellowish, bluish mud, with the inclusion of organic macrofossils (mosses) in the range of 1.16–0.48 m. The variations of OM are from ~3% to ~7% (1.16–0.52 m) and from ~2% to ~10% (0.52–0.00 m). MS values are generally low (~45– 230). A very low sand content (less than 2%) registered at the depths of 0.65–0.00 m, and an increased sand content (up to ~11%) measured at the depths of 1.16–0.65 m. The lamination is not uniform: the thickness of olive layers is 3–20 mm, dark gray 2–10 mm, yellowish 7–10 mm, bluish 3–5 mm.

3.3. Geochemical composition

Results of geochemical analysis are presented in table 2, figure 4. The values of three main factors F1, F2, F3 were obtained by statistical data processing of selected chemical elements with high correlations. F1 values characterize an antagonism of the elements associated with the organic component of sediments (Mg, S) to the group that are part of aluminosilicates, quartz, zircon (Ca, Ti, K, Si, Zr, Al) and enter the reservoir with a lithogenic component (clay, silt, sand). F2 values correlate with the redox conditions in the reservoir where Zr and Mn accumulate mainly in an oxidizing environment, while S, P, Fe accumulate in a reducing environment. F3 values characterize the processes of biophilic elements accumulation (Cu, Zn) associated with organic-rich silty sediment complexes, and the processes of Al, Si, P enrichment of sediments, reflecting the mineral contribution. Factor analysis showed that the contribution of these most significant factors to the dynamics of elemental composition and thus to the sedimentation processes is 36%, 8.15%, and 7.32%, respectively.

To compare the results of geochemical analysis with other characteristics determined mainly for every 2 cm of the sedimentary sequence, the factor scores for each 20 mm were determined. Figure 4 shows the dynamics of factor loading (F1, F2, F3) – a coefficient that reflects how strongly each indicator influences a given factor. Factor loading can be positive or negative, indicating the direction of this influence. The analysis of their variations revealed eight main intervals of different sedimentation conditions (Gz 1 – Gz 8).

Gz 1 (4.24–4.17 m). Positive F1 values and negative F3 values indicate the accumulation of sediments in the reducing conditions.

Gz 2 (4.17–3.93 m). F1 values are mostly negative, indicating the predominance of oxidative conditions.

Gz 3 (3.93–3.50 m). A significant rise in F1 values and a decrease in F2 values reflect distinct reducing conditions in the lake.

Gz 4 (3.50–3.45 m). In this short interval fluctuations are observed that culminate in a sharp increase in F2 values, an increase in F3 and F1 values, which reflects a rapid increase in the proportion of mineral material.

Gz 5 (3.45–2.70 m). F1 values vary and are predominantly negative, but with a tendency to increase towards the top of the interval, F2 values are generally stable and F3 values are positive and consistently increase from the bottom up, which reflects the overall predominance of oxidative processes and the influx of terrigenous material with the accumulation of silt fraction.

Gz 6 (2.70–2.53 cm). The values of all factors increase which may point to an increase in the biophilic elements content and the predominance of reducing conditions.

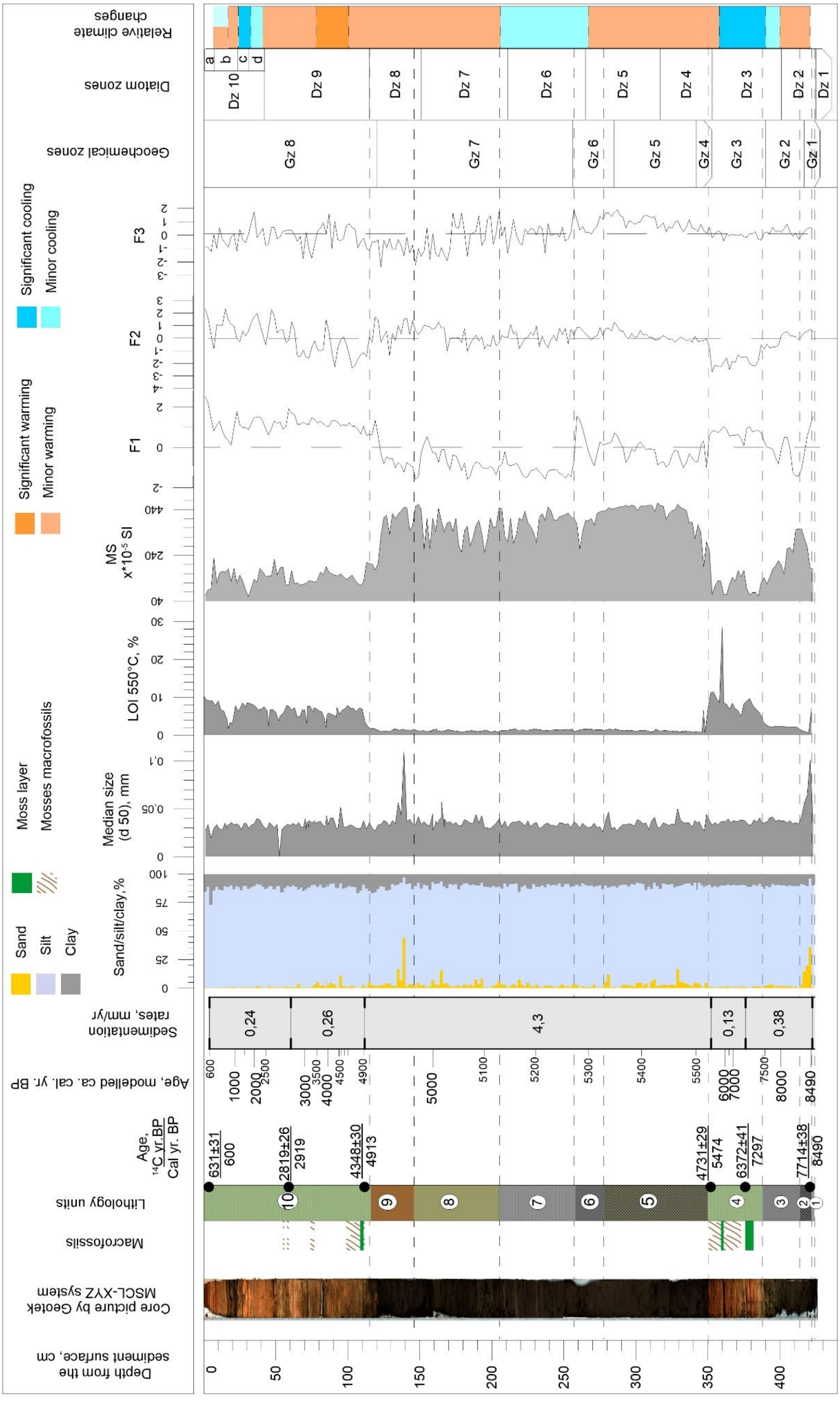

Fig. 4. The results of litho-, bio-, geochemical, chronostratigraphic analyses for the bottom sediments of Lake Geographensee with interpretation of relative climatic changes.

Рис. 4. Результаты лито-, био-, геохимического, хроностратиграфического анализа донных отложений озера Географов с интерпретацией относительных климатических изменений.

Gz 7 (2.53–1.20 m). The clear predominance of low negative F1 values and numerous F2, F3 values variations near the average in the lower part, with a slight increase in F2 values and a decrease in F3 values in the upper part of the interval indicate, in general, oxidative conditions, and prevailing accumulation of terrigenous material.

Gz 8 (1.20–0.00 m). Sedimentation occurred mainly under reducing conditions as evidenced by F1 high positive values and F2 low values in the lower part of the interval, although in its upper part some high amplitude fluctuations of the values of F2, F3 indicate probable changes in the conditions of sedimentation.

3.4. Diatom flora

The diatom flora of Lake Geographensee sediments includes 103 species of 34 genera of the *Bacillariophyta* division. With the exception of three planktonic species of the genus *Aulacoseira*, all species are benthic; freshwater and freshwater-brackish diatoms predominate; marine diatoms have not been found. The distribution of diatoms in the sedimentary sequence is uneven; there are intervals with single or no diatoms. In the lower intervals (4.24–2.07 m), the diatom valves are mostly thin and small in size. Large diatoms appear above 2.07 m. Analysis of changes in the quantitative and species composition of diatoms allows us to identify ten diatom zones (Dz 1 – Dz 10) and four subzones in the upper zone (Dz 10a – Dz 10d) (fig. 4, 5). In Dz 1 (4.24–4.19 m) only a few valves of freshwater diatoms *Hippodonta hungarica, Planothidium cf. frequentissimum, Achnanthidium maritimo-antacticum* and others were found that do not form a distinct diatom assemblage.

Dz 2 (4.19–3.95 m) is characterized by diatom assemblages with high abundance of freshwater benthic diatoms dominated by *Planothidium cf. frequentissimum* (up to 52% of the total diatom species composition), freshwater-brackish, very finely silicified *Nitzschia pale*a (up to 40%). The subdominant group includes freshwater-brackish, bottom alkaliphile *Hippodonta hungarica* (up to 26%) with a pH optimum greater than 8 (Van de Vijver et al., 2002), *Fragilaria capucina* (up to 12%), aerophilic *Humidophila contenta* (up to 4%). The number of epipelic and epiphytic diatoms is set in equal proportions. At the very top of the zone, only single valves of diatoms were found.

Dz 3 (3.95–3.50 m) is rich in freshwater diatom assemblages. Freshwater diatoms account for up to 94.4%. Among benthic species epiphytic makes up 49.9–80.6% and epipelic 17.0–51.1%, pH-neutral species prevail. *Staurosirella antarctica* (up to 56%), which is very common and dominant in stagnant waters, has a pH optimum 7.2 (Van de Vijver et al., 2002). It is one of the pioneer species of lake settlement during deglaciation that replaces freshwater *Planothidium* cf. *frequentissimum* that dominated in Dz 2 zone. The subdominants are *Chamaepinnularia* sp. 1 (up to 30%), *Achnanthidium maritimo- antacticum* (up to 29%). At a depth of 3.61–3.65 m, single benthic freshwater and brackish- freshwater diatoms with a predominance of *Halamphora veneta* were found.

Dz 4 (3.50–3.17 m) is characterized by the occurrence of a few freshwater benthic diatoms, mainly *Hippodonta hungarica, Planothidium cf. frequentissimum, Staurosirella antarctica,* the small valves of which bear traces of dissolution, the absence of morphological elements, and lightened colors.

Dz 5 (3.17–2.65 m) is dominated by *Staurosirella antarctica* (up to 35%) and freshwater species *Nitzschia* cf. *perminuta* (up to 15%) diatom assemblages that are characteristic of temporary reservoirs (Kopalová, Van de Vijver, 2013), and *Planothidium australe* (up to 15%). The number of diatoms increases sharply with a maximum at the lowermost interval (3.14–3.17 m) where the number of freshwater-brackish

Table 2. Factor scores in PCA
Таблица 2. Баллы по факторам в PCA

	Factor 1	Factor 2	Factor 3
Fe	–0.790550	–0.242644	0.089994
Ni	0.089059	–0.411669	–0.328992
Cu	–0.159523	–0.323258	0.707654
Zn	–0.444952	–0.232525	0.567079
Br	–0.037304	–0.010907	0.119309
Rb	–0.014686	0.049818	0.151814
Zr	–0.824049	0.153039	0.192757
Pb	–0.157907	–0.135469	–0.042378
Mg	0.259203	0.307293	0.072564
Al	–0.777859	–0.053973	–0.387784
Si	–0.900952	0.043683	–0.270312
P	–0.575538	–0.356814	–0.222761
S	0.051374	–0.832627	–0.095837
K	–0.888791	–0.003167	–0.028556
Ca	–0.911991	0.179650	0.085656
Ti	–0.933669	0.179792	0.061175
Mn	–0.676964	0.218239	–0.059026
Co	–0.394279	–0.067525	–0.018028

diatoms is also increased (30%) due to *Hippodonta hungarica*. Above, freshwater diatoms account for up to 99%. Among benthic species epiphytic makes up 49.3–89.0%, and epipelic 11.0–50.7%. In the intervals 3.13–3.01 m and 2.97–2.89 m single diatom valves were found, and in the interval of 2.77–2.73 m there were no diatoms.

Dz 6 (2.65–2.07 m) includes rare valves of *Chamaepinnularia* sp.1, *Fragilaria capucina*, *Planothidium austral* and other diatoms.

Dz 7 – Dz 10 are characterized by diatom assemblages with high abundance and diversity. Diatom valves are large in size.

Dz 7 (2.07–1.51 m) is dominated by *Fragilaria capucina* (up to 62%), which often lives in stagnant waters with optimum pH 7.2 (where it can dominate the entire flora), and can also develop in moist mosses (Van de Vijver et al., 2002); *Hippodonta hungarica* (up to 38.5%); *Nitzschia* cf. *perminuta* (up to 35.8% in the upper intervals of the zone). Epiphytes predominate at the very bottom of the zone, epipelic diatoms predominate in the upper intervals (up to 84%). At the depths of 1.99–1.92 m only 4 diatom valves were found.

Dz 8 (1.51–1.15 m) is dominated by *Hippodonta hungarica* (up to 63.8%); *Planothidium lanceolatum* (up to 34%) circumneutral, preferring water with a very low amount of phosphates, crenophile (Van de Vijver et al., 2002); *Staurosirella antarctica* (up to 18%). Epipelic and epiphytic diatoms occur in approximately equal proportions.

Dz 9 (1.15–0.42 m) is characterized by preveiling freshwater epiphytic species, among which the circumneutral *Achnanthidium maritimo-antacticum* acounts for up to 54% and alkaliphilic *A. australexiguum* acounts for up to 27.2%. Epipelic species are Navicula cremerie (up to 17%), brackish-freshwater *N. gregaria* (up to 29%), Hippodonta hungarica (up to 24%), Staurosirella antarctica (up to 25%). Among the accompanying species is Frustulia vulgaris, a rare species characteristic of flowing waters with pH = 7.7 (Van de Vijver et al., 2002), freshwater-brackish *Halamphora veneta* (up to 9.7%) and *Planothidium australe* (up to 7%).

Dz 10 (0.42–0.0 m) has the largest diatom valves present and is dominate by epipelic species. Four subzones are identified with in Dz:

Subzone Dz 10-d (0.42–0.31 m) consists of brackish-freshwater species *Navicula gregaria* (up to 39.5%) demonstrating the maximum amount in the entire sedimentary sequence. It is accompanied by *N. cremeri* (up to 17%) and *Staurosirella antarctica* (up to 18%).

Subzone Dz 10-c (0.31–0.23 m) is identified by a dominance of a large strongly silicified *Craticula subpampeana* (up to 41.5%) accompanied by the epiphyte *Gomphonema* sp. (up to 16%) which reaches the maximum quantitative values here, and *Staurosirella antarctica* (up to 12.1%). The amount of *Navicula gregaria* sharply decreases (down to 1% versus 40% in Dz 10-d), while the content of aerophilic *Humidophila contenta* and reophilic *Frustulia vulgaris* increases.

Subzone Dz 10-b (0.23–0.07 m) includes planktonic species *Aulacoseira* cf. *ambigua* (9.3%) and *A.* aff. *granulata* (1%) which is rare for Antarctic lakes. *Achnanthidium maritimo-antarcticum*, *Navicula gregaria*, *N. sgemegi*, *Nitzschia* cf. *perminuta*, *Stauroneis*

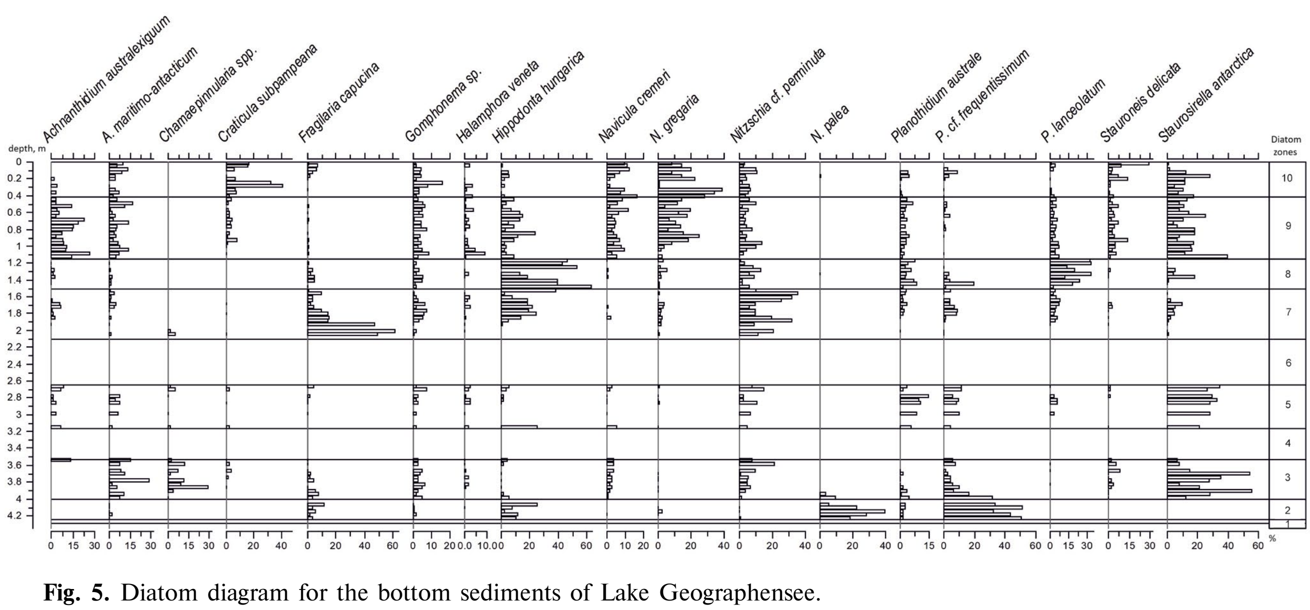

Fig. 5. Diatom diagram for the bottom sediments of Lake Geographensee.

Рис. 5. Диатомовая диаграмма колонки донных отложениях озера Географов.

delicata, *Staurosirella antarctica* are also noticeable in diatom assemblages.

Subzone Dz 10-a (0.07–0.00 m) is characterized by prevailing of *Stauroneis delicata* (up to 30%), *Craticula subpampeana* (up to 16.6%), Navicula gregaria (up to 14.8%). There is also a significant number of aerophilic species of *Stauroneis delicata*, *Humidophila contenta*, *Luticula muticopsis*.

4. DISCUSSION

According to earlier research (Mäusbacher et al., 1989; Watcham et al., 2011; Verkulich et al., 2012; Barion et al., 2023) the deglaciation of the southern part of Fildes Peninsula where Lakes Geographensee and Jurasee are located began about 11,000 cal. yr BP and was rapid. The catchments of these lakes do not bear traces of the reemergence of glaciers. The position of the lakes above the Holocene marine transgression limit (Polishchuk et al., 2016) and the absence of marine diatoms in their sediments (Mäusbacher et al., 1989; this study) allow the possibility of the influence of marine waters in lakes during the Holocene only through aerosols. Thus, the formation of the sedimentary sequence of the freshwater Lake Geographensee in the Holocene was generally determined by changes in climate, conditions in the catchment area (e.g. the area of the catchment and snowfields on it, the surface sediments composition, vegetation, erosion and other processes) and lake parameters (small size and shallow depth, possible drainage through outlet channel).

The studied characteristics of Lake Geographensee sediments contain integrated, indirect information about changes in the mentioned above factors affecting the ice regime, temperature, turbidity, chemical composition of the lake water and the development of biota. At the same time, the causal relationships between external influences and the internal condition of this small Antarctic lake are complicated. For example, a significant increase in summer temperatures should lead to warming of lake waters, but it also could lead to large volumes of cold meltwater runoff into the lake, contributing to an overall decrease in the water column temperature.

In order to identify the main stages of changes in sedimentation in Lake Geographensee and emphasize the role of climate the variations in sediments characteristics are compared according to the sedimentary sequence. Note that the simulated time limits used are approximate due to the indisputable presence of unaccounted-for changes in the sedimentation rate.

4.1. The initial stage of the lake – ca. 8500 cal. yr BP (U 1, 4.24–4.22 m depth)

Thin-laminated mud ca. 8490 cal. yr BP old at the base of the sedimentary sequence (fig. 4) is characterized by an increased content of sand, the presence of organic matter and a high value of a geochemical factor F1 (Gz 1). This suggests sedimentation in an already existing lake, in the conditions of the lake annual release from the ice cover and the relatively warm summer season. Rare diatoms do not form a diatom assemblage (Dz 1), which is typical for the initial stage of development of a postglacial reservoir.

Lake Geographensee was formed, apparently, later than the neighboring Lake Jurasee, in which about 35 cm of thin-laminated and 5 cm of homogeneous silt were accumulated between sediments with organic matter, aged 8700±300 yr BP (ca. 9700 cal. yr BP) and glacial till (Mäusbacher et al., 1989; Matthies et al., 1990). It can be assumed that around ca. 9700–8500 cal. yr BP climatic conditions generally favored the deglaciation of catchments and both lakes formed.

4.2. ca. 8500–7450 cal. yr BP (U2, U3; 4.22–3.88 m depth)

After the change of a thin sandy-mud layer (U2) to a thick obscurely laminated mud (U3) the latter has a generally low sand content as well as a consistent decrease in MS values from the initially high value. This may indicate a gradual decrease in the allochthonous material proportion. Diatom assemblages (Dz 2) with dominant species of the genus *Planothidium* indicate sedimentation in a shallow (Björck et al., 1991) cold- water reservoir with a neutral pH and, possibly, increased water mineralization. The presence of aerophilic diatom species indicates a likely increase in the ice-free catchment area. Apparently, at the very beginning of this period the climate was relatively warm and the lake was free of ice cover for quite a long time in the summers. This is confirmed by the low values of factor F1 (lower part of Gz 2). Oxidative conditions in the lake at that time could be facilitated by ice-free conditions in which mixing and oxygen saturation of waters under wind influence increased. As the end of the period approached it became colder.

4.3. ca. 7450–5600 cal. yr BP (U 4, 3.88–3.50 m depth)

Very low sedimentation rates, low MS values and content of the sand fraction in U4 indicate a limited terrigenous material supply into the lake. This could be caused by a cooling with a corresponding increase in the ice cover duration and decrease in erosion in the lake's catchment area. Diatom assemblages (Dz 3) also indicate cold, stagnant conditions, a likely decrease in the lake depth. Due to a low summer warming and the prolonged presence of ice cover that led to a decrease in water mixing the oxygen content in the lake decreased and reducing conditions appeared (Gz 3). Anaerobic environment could contribute to the preservation of freshwater mosses contained in sediments and increasing of the OM content values.

The development of mosses under such conditions is possible (Priddle, Heywood, 1980) as in Antarctic lakes mosses may colonize the bottom even during initial proglacial or oligotrophic stages and low light intensities, when nutrient content is higher at the bottom than in the water column, the influxes of terrigenous material is limited, and bottom sediment is stable.

The conclusion about significant cooling is supported by the results of study of Lake Mondsee sediments (fig. 1), where mosses and diatom complexes indicate reduced allochthonous input due to extensive lake ice-cover or colder summer conditions between ca. 7200 yr BP (ca. 8000 cal. yr BP) and ca. 4700 yr BP (ca. 5400 cal. yr BP) (Schmidt et al., 1990). In addition, the increased Mo and U content found in the sediments of Lake Yanou (fig. 1) dated ca. 7300–7100 cal. yr BP was explained by anoxic conditions, the cause of which could be the lake harsh ice conditions (Watcham et al., 2011).

4.4. ca. 5600–4900 cal. yr BP (U5–U9, 3.50–1.16 m depth)

The middle part of the sedimentary sequence (U5–U9) differs sharply from others in general by high sedimentation rates, increased sand content, high MS values, low OM content, and predominantly low values of the geochemical factor F1 (fig. 4). Periods of very rapid sediment accumulation with a low organic matter content were also revealed for other Fildes Peninsula lakes which were not affected by Holocene transgression (fig. 1): from ca. 4700 yr BP (ca. 5400 cal. yr BP) lasting more than a thousand years for the Lake Mondsee (Schmidt et al., 1990); ca. 5100–4300 yr BP (ca. 5800–4800 cal. yr BP) for Hotel Lake (Tatur et al., 2004); ca. 5000–4400 yr BP (ca. 5800–5000 cal. yr BP) for Lake Jurasee (Mäusbacher et al., 1989).

This coincidence points to the regional scale of events that provided a sharp increase in the volume of mineral material entering the lakes. Since there is no evidence of glaciers growth in the catchments of these lakes during this period, the reason for the increase in erosion and movement of the material into reservoirs could be an increase in temperatures and an increase in the duration and humidity of the summer season (Mäusbacher et al., 1989; Schmidt et al., 1990). This conclusion is indirectly supported by suggested prolong duration of open-water conditions in the bays off the Fildes Peninsula in the summer that occurred between ca. 5900–5700 cal. yr BP and ca. 4850–4750 cal. yr BP (Watcham et al., 2011).

The beginning of this period also coincides with activation of volcanism (most likely on Deception Island (Roberts et al., 2017)) and the tephra fallout. Distinct tephra layers were found in sediments ca. 5500 cal. yr BP old in Lake Kiteschsee (Barion et al., 2023), ca. 5200 yr BP (ca. 5950 cal. yr BP) in Lake Jurasee (Matthies et al., 1990), ca. 5100 yr BP (ca. 5900 cal. yr BP) in Lake Hoteriasee (Tatur et al., 2004). In this regard, the 1.5 m thick sediments of the ca. 5900–4500 cal. yr BP period in Lake Hoteriasee were interpreted as redeposited tephra, the arrival of which strongly influenced the sedimentation conditions and the lake diatom flora (Tatur et al., 2004). Although there are no distinct layers of tephra in the U5 – U9 sediments of Lake Geographensee, its presence here is undeniable (Matthies et al., 1990). This may be one of the explanations why the color scheme of these deposits is different from other units, as well as the obvious U5 – U9 silt fraction predominance during almost the entire accumulation period (fig. 4), which is discussed below.

The local reason for the increase in the rate of sedimentation in Lake Geographensee could be explained by its connection with Lake Jurasee, when the water level in Lake Jurasee could have reached altitudes of about 50 m a.s.l. (fig. 2). The connection between the lakes is indicated by presence of the old, dry channels between them. Through these channels Lake Geographensee could have received influx of water and sediments from Lake Jurasee located above. This event may explain why sedimentation rates during this period increased in Lake Geographensee by almost 40 times, while in Lake Jurasee by 20 times (Mäusbacher et al., 1989).

By the gross we assume that variations in sediment characteristics in U5 – U9 reflect changes in sedimentation conditions due to short-term climatic fluctuations on the general background of warming, tephra accumulation, and the outflow of Lake Jurasee' waters into Lake Geographensee.

Below follows the description of five substages of the period.

4.5. ca. 5600–5320 cal. yr BP (U5, 3.50–2.78 m depth)

From U4 to U5, about ca. 5600 cal. yr BP, hydrology of Lake Geographensee had changed dramatically which is reflected in the disappearance of aquatic mosses, the almost complete disappearance of diatoms (Dz 4), sharp decrease in the OM amount, sharp increase in MS values, an increase in the content of sand in the U5 sediments (fig. 3, 4, 5), predominance of the oxidizing conditions, an increase in the proportion of allochthonous material (Gz 4, Gz 5) and in the sedimentation rate. The accumulation of lake sediments with such characteristics could be ensured by a long ice-free conditions, high turbidity, active mixing with low temperature water in the summer seasons, i.e. under conditions of warming, increased cold meltwater runoff, increased erosion, and removal of terrigenous material from the catchment surface into the lake.

However, it is difficult to explain warming of such a high amplitude leading to a 40-fold increase in the amount of mineral material delivered from a small catchment area to the lake. In addition, the obvious predominance of silt fraction in sediments casts doubt on the multiple increase in energy and erosive ability of summer meltwater. Instead, we assume that the abundant tephra fall out also had a great influence on the accumulation of U5. It could multiply the amount of unbound, fine-grained sediment in the catchment area and, thus, increase the volume of material washed into the lake, and enhance the contaminated snow surfaces melting. During this period, the merger of Lakes Geographensee and Jurasee or beginning of water outflow from Lake Jurasee to Lake Geographensee probably had occurred. Besides the increased supply of the meltwater, the rise in lakes level at that time could also had been caused by the presence of snow-ice dams at the exits from the valleys towards the sea.

Diatom assemblages were found intermittently in the Lake Geographensee sediments at the depths of 3.13–3.01 m and 2.97–2.89 m (lower part of Dz 5), which probably reflects the presence of short-term periods with a decrease in the water column turbulence and turbidity around ca. 5430 cal. yr BP.

4.6. ca. 5320–5270 cal. yr BP (U6, 2.78–2.58 m depth)

In the sediments of this short period of time a low content of sand fraction was observed and an interval with a clear decrease in MS values was recorded along with a noticeable increase in values of all geochemical factors (Gz 6). Diatom assemblages were found only in sediments at the depths of 2.73–2.65 m (top of Dz 5). Sediments lacking diatoms were deposited during unfavorable conditions for the diatom's development, such as possible decrease in the reservoir level (lowest part of Dz 6). Apparently, sedimentation at this time took place under slight cooling conditions and an increase in the ice cover duration. Together with the continued supply of abundant silt material during summer it stimulated the appearance of reducing conditions in the reservoir in winter.

4.7. ca. 5270–5130 cal. yr BP (U7, 2.58–2.05 m depth)

The U7 deposits differ from U6 by a slightly increased sand fraction proportion and consistently low values of the geochemical factor F1 (lower part of Gz 7), indicating an increase in the terrigenous material inflow and the predominant oxidative conditions. This pattern indicates a slight warming and an increase in the ice-free period. At the same time, the discontinuity of sediment intervals with a high sand content, high amplitude fluctuations in MS values, the appearance of lamination indicate the alternation of periods with different sedimentation rates, ice and temperature conditions.

Almost complete absence of diatoms in Dz 6 indicates unstable, cold-water hydrological conditions and high turbidity of the water. The instability of hydrological conditions in Lake Geographensee could have been enhanced by the increase and decrease in the volume of water flow from Lake Jurasee during relative warming and cooling intervals.

4.8. ca. 5130–4970 cal. yr BP (U8, 2.05–1.46 m depth)

A discretely distributed but significant increase in the sand fraction proportion in U8 sediments (up to 12%) may point to a periodic increase in the energy and erosive ability of streams flowing into the lake due to more active snow melt in the summer seasons. It could also mean a decrease in the amount of tephra at the catchments surface due to its previous flushing. A reduction in the volume of fine-grained tephra material entering the lake could contribute to an increase in water transparency, which, together with an increase in summer heating favored the development of diatom flora. Changes in the U8 sediments from the bottom up in the species and quantitative composition of diatoms (Dz 7) indicate a change in the pH of the water from neutral to alkaline.

An increase in the values of F1 and F2 factors (upper part of Gz 7) and a decrease in the sand content in the upper part of U8, are associated with a short decrease in the volume of meltwater entering the lake and less water turbulence, that led to an increase in the biogenic elements concentration. This is consistent with the first appearance of larger, more silicified diatom valves in Lake Geographensee' sediments (Dz 7).

The MS values in the U8 sediments show 10 sharp, fairly regular fluctuations over 160 years which may coincide with climatic rhythms. It is likely that the flow of water from Lake Jurasee to Lake Geographensee was greatly reduced during colder periods and increased sharply during warmer periods, when up to 50 mm thick layers were formed in the U8 sediments.

4.9. ca. 4970–4900 cal. yr BP (U9, 1.46–1.16 m depth)

U9 deposits have a high content of sand fraction (up to 49%), consistently high MS values, and low values of geochemical factors. All these characteristics are an obvious indicator of the active influx of terrigenous material due to an increased meltwater runoff during warm summers. The reduced proportion of silt is probably related to the depletion of fine tephra material in the catchment area. The diatom assemblages (Dz 8) suggest that the U9 deposits accumulated during an increased meltwater inflow (rheophilic diatoms may indicate increased melting), in a pH alkaline-neutral environment.

However, the sharp change in sedimentation, expressed in a decrease of sand content, a drop in MS values, and an increase in the geochemical factors values (upper part of Gz7) were documented at the very end of this period. Apparently, at this time, separate drainage channels from Lakes Geographensee and Jurasee towards the sea were finally formed, which led to the loss of connection between the lakes.

4.10. ca. 4900–600 cal. yr BP (U10, 1.16–0.00 m depth)

In contrast to U5–U9, the laminated deposits of U10 generally have a low content of sand fraction, low MS values and high values of factor F1 (Gz 8). Together with a sharp drop in the sedimentation rate these characteristics indicate a significant reduction in the flow of terrigenous material into the lake. It can be assumed that such a reduction could be caused not so much by climatic fluctuations but by a change in the catchment area due to the following reasons:

1. isolation of Lake Geographensee and a corresponding cessation of supply from Lake Jurasee;
2. the disappearance of tephra in the catchment area due to being flushed in the lake earlier;
3. the decrease of snowfields in the catchment area.

A decrease in the summer meltwater (and terrigenous material) inflow should have led to a decrease in the lake turbulence and turbidity, to stabilization of its hydrological regime, calm water over the bottom, and a gradual increase in water mineralization. This, in turn, would favor the development of lacustrine biota, which is expressed in the U10 sediments by an increased OM content, as well as the presence of diatom flora with larger and more silicified valves (Dz 9, Dz 10) than in the sediments of the previous period.

Climatic fluctuations undoubtedly also affected the state of the lake and were documented by variations in the characteristics of U10 sediments, primarily changes in diatom assemblages (fig. 4, 5). The diatom assemblage Dz 9 at the depths of 1.16–0.42 m (ca. 4900–2500 cal. yr BP) indicates sedimentation in relatively warm conditions in alkaline environment and high level of mineralization of water. The presence of a rare *Frustulia vulgaris* species, characteristic of flowing waters with a pH of 7.7 (Van de Vijver et al., 2002), confirms the possibility of an increase in meltwater supply during some time periods. This is also consistent with the presence of sand layers.

In contrast, mosses were found only in those intervals of U10 where the sand content is low, which demonstrates their preference for stable hydrological conditions. Higher water temperature in the lake in the summer and an increase in the nutrients intake detected during ca. 4800–3400 cal. yr BP according to F2 and F3 values (Gz 8, depths 1.01–0.78 m). This is supported by the results of a study of Lake Mondsee and Lake Tiefersee sediments (fig. 1), suggesting the existence of relatively warm conditions in the Middle Holocene up to ca. 3200 yr BP (ca. 3400 cal. yr BP) (Schmidt et al., 1990).

Four subzones were identified in the diatom zone Dz 10. This zone covers the upper 42 cm of the sedimentary sequence and characterized by extremely low sand content. The subzones correspond to the changes in habitat conditions of diatoms. In Dz 10-d (0.42–0.31 m depth, ca. 2400–1800 cal. yr BP) the diatom assemblages are dominated by brackish-freshwater species *Navicula gregaria*, that prefers water of increased mineralization. All geochemical parameters showed higher values while the values of MS decreased in this subzone (fig. 4). Such characteristics indicate an increase in the period of the ice cover, a decrease of water exchange, the predominance of reducing conditions in the lake, and likely corresponded to cooling compared to the previous time period.

Diatom assemblages in Dz 10-c (0.31–0.23 m, ca. 1800–1200 cal. yr BP) are dominated by *Craticula subpampeana*, common in lakes with low amounts of phosphorus, nitrates and sulfates (Van de Vijver et al., 2010), and *Gomphonema* sp., with a noticeable counts (up to 17%) of aerophilic diatom species, and the presence of rheophilus *Frustulia vulgaris*. The presence of aerophilic and rheophilic species may indicate the entry of diatoms into the lake from soils and mosses by temporal run-off that do not move a lot of allochthonous material. The dominant species indicate a stable or falling lake level (Van de Vijver et al., 2002). A distinct drop in the F2, F3, and MS values in these sediments also indicates a decrease in the input of allochthonous material into the lake. It can be assumed that sedimentation occurred in relatively cold conditions. Results of study of bottom sediments from Lake Yanou also assumed the cooling during ca. 1700–1300 cal. yr BP (Roberts et al., 2017).

Planktonic species of diatoms were found in the Dz 10-b diatom complex at the depths of 0.23–0.07 m (ca. 1200–800 cal. yr BP). Their habitat is primarily associated with warmer water and increased concentration of nutrients in the surface layer of the reservoir (Van de Vijver et al., 2002). The possibility of relative warming during this period is confirmed by a distinct decrease in F1 values along with an increase in F2, and MS values, which indicates an increase in the proportion of allochthonous material in sediments (the content of OM here drops sharply) due to increased erosion in the catchment area, the delivery of material to the lake during longer and warmer summers than in the previous period. The quantitative temperature reconstruction performed for Lake Yanou sediments using biomarkers (Roberts et al., 2017) assumed that sedimentation occurred under relatively warm conditions during ca. 1300–900 cal. yr BP period.

The Dz 10-a subzone in the upper 7 cm of the sedimentary sequence (ca. 800–600 cal. yr BP) has no distinct dominant species in diatom assemblages, contains many aerophilic species and large-sized diatoms, indicating an increased amount of nutrients in the lake. The sediments are characterized by amplitude fluctuations of high F2 and MS values, an increase in F1 values, and the OM content. Apparently, the climatic conditions of this period were slightly colder than of the previous one, but still generally warm. Probably, minor climatic fluctuations occurred during this short period, which was also recorded in Lake Yanou' sediments (Roberts et al., 2017).

5. CONCLUSIONS

The relative climatic changes reconstructed from Lake Geographensee sediments can be ranked by amplitude and compared with the results of similar studies of other lakes on the Fildes Peninsula (Barion et al., 2023, Mäusbacher et al., 1989; Schmidt et al., 1990; Tatur et al., 2004; Watcham et al., 2011; Verkulich et al., 2012; Roberts et al., 2017). When cooling or warming intervals coincide in reconstructions of several lakes, we can assume that these paleoclimatic events occurred on a regional scale and with significant amplitude. Based on this assumption the most prominent cooling stages took place in ca. 7500–5600 cal. yr BP (with a maximum cold ca. 7300–7000 cal. yr BP), and probably ca. 1800–1200 cal. yr BP periods. The warming stage took place during ca. 4800–3400 cal. yr BP. The rest of the climatic fluctuations were less prominent: minor relative warming could have occurred during ca. 8500–8000 cal. yr BP, ca. 5600–5300 cal. yr BP, ca. 5130–4800 cal. yr BP, ca. 3400–2400 cal. yr BP and ca. 1200–800 cal. yr BP periods; minor relative cooling had occurred during ca. 8000–7500 cal. yr BP, ca. 5300–5130 cal. yr BP, ca. 2400–1800 cal. yr BP periods. The ca. 800–600 cal. yr BP period probably included both short term relative cooling and warming. Thus, the results of this study associated with paleolimnological information collected in the Fildes Peninsula earlier allows to obtain the most detail and continuous paleoclimatic reconstruction in King George Island, providing a foundation for broader understanding of the Holocene climate change in the West Antarctica.

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КЛИМАТИЧЕСКИЕ КОЛЕБАНИЯ СРЕДНЕГО–ПОЗДНЕГО ГОЛОЦЕНА, ЗАФИКСИРОВАННЫЕ В ДОННЫХ ОТЛОЖЕНИЯХ ОЗЕРА ГЕОГРАФОВ (ПОЛУОСТРОВ ФАЙЛДС, ОСТРОВ КИНГ ДЖОРДЖ, ЗАПАДНАЯ АНТАРКТИКА)[#]

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Статья посвящена палеоклиматической реконструкции изменений окружающей среды в голоцене. Для решения этой проблемы было проведено исследование донных отложений озера Географов, расположенного на полуострове Файлдс, остров Кинг Джордж, Западная Антарктика. Озеро расположено выше максимального уровня морской трансгрессии голоцена, поэтому донные отложения озера представляют собой непрерывный природный архив последних 8500 кал. л. н. Представлены результаты литологического, геохимического, диатомового, гранулометрического анализов, потерь при прокаливании, а также статистической обработки данных и радиоуглеродной хронологии донных отложений. Выявлены существенные и незначительные этапы изменения климата. Значительное потепление произошло около 4800–3400 кал. л. н., незначительные интервалы потепления установлены ~8500–8000, ~5600–5300, ~5130–4800, ~3400–240, ~1200–800 кал. л. н. Этап существенного похолодания произошел ~7500–5600 кал. л. н., с пиком холодного периода около 7300–7000 кал. л. н. и, возможно, ~1800–1200 кал. л. н. Незначительные этапы относительного похолодания происходили в следующие периоды: ~8000–7500, ~5300–5130, ~2400–1800 кал. л. н. Краткосрочные этапы относительных похолоданий и потеплений имели место в период около 800–600 кал. л. н. Принимая во внимание отсутствие в рассматриваемом регионе ледников, подходящих для получения палеоклиматических данных, выполненные палеолимнологические исследования обеспечивает основу для более широкого понимания изменения климата в голоцене в Западной Антарктике.

Ключевые слова: климат, голоцен, озерные отложения, литология, радиоуглеродный анализ, магнитная восприимчивость, геохимия, диатомовые водоросли, седиментация

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