Ecosystem of mountain oligotrophic Lake Yaktykul (Bannoe) (Southern Urals, Russia): shifts and drivers for over 300 years

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Abstract

This research is focused on the paleolimnological study of the mountain-steppe oligotrophic Lake Yaktykul (the Southern Urals). The study objective is to determine changes in the lake ecosystem over the past 300 years in response to the global warming and increasing anthropogenic pressure. The lake sediment cores of the southern relatively deep-water and northern shallower parts of the lake were studied by diatom, chironomid, palynological, isotopic ($\delta^{13}C$) and elemental (trace elements, total organic carbon and nitrogen) analysis. The regional diatom transfer function was used for reconstructions of a total phosphorus (TP) content. The variations in July temperature and lake depth since AD 1718 were estimated by the chironomid analysis. Electrical conductivity was determined based on the diatom analysis data and the geochemical multiple regression model. The general boundaries of changes in the lake ecosystem in the deep and shallow parts were outlined: a decrease in the trophic status of the lake in AD 1840-1900, a decrease in lake depth and an increase in aquatic vascular plants in AD 1900-1970, an increase in depth and violent fluctuations in TP in AD 1970-1996. The beginning of the twenty-first century was marked by a greater stratification and a reduced TP in the epilimnion, in both southern and northern parts of the lake. The main changes in lake ecosystem were associated with climate. The multivariate analysis demonstrated a statistically significant relationship of diatom assemblages to temperature and precipitation variations. Small cyclic diatoms and planktonic pennate diatoms are directly correlated to an average annual temperature. Total phosphorus in the deep part inversely correlated with a temperature in August. No eutrophication trend related to the increasing anthropogenic impact was discovered in Lake Yaktykul. The mining and metallurgy effect was recorded only in the increasing enrichment of sediments in potential toxic elements.

Keywords: climate warming, chironomides, diatom assemblage, human impact, lake sediments core, oligotrophic lake, palynomorphs, quantitative reconstruction, isotopic composition ($\delta^{13}C$) of organic matter

1. Introduction

The freshwater lakes which exert important economic and recreational impacts undergo around the world a rapid pollution and eutrophication under the global warming and increasing human impact. The lakes of the Ural industrial region are an important object for studying the combined influence of climatic and anthropogenic factors on the lake ecosystems. Due to the fact that the long-term monitoring has been carried out only for some lakes in the Urals and only since the mid-twentieth century, it is possible to reconstruct the time and the lake ecosystem response to various factors with the help of the paleolimnological studies.

The paleolimnological study of lakes in the forest zone of the Middle and Southern Urals made it possible to reveal shifts in diatom assemblages and changes in diatom indices and planktonic diatoms in the nineteenth and twentieth centuries (Maslennikova et al., 2023b). Despite the contamination by PTEs, lakes Turgoyak, Tavatui, and Syrytkul experienced an increase in trophic state and in planktonic diatoms. Oligotrophication was inferred only in the record of Lake Ufimskoe which was the most contaminated by PTEs, but marked by the least other human impact. It is concluded that diatom assemblages in the studied lakes primarily record the influence of the local human activity, rather than the global warming. Industry-related acidification and higher PTEs altered the lake development only under the condition of weak influence of other human activities . Sedimentary diatom assemblages from several Northern Ural lakes show distinct changes involving planktonic diatoms in the twentieth century, likely due to a temperature increase in June and September, that extended a duration of the ice-free season (Solovieva et al., 2008). Paleolimnological reconstructions based on the diatom analysis of sediment cores from the Polar Urals made it possible to reveal changes in lakes over the past 100-150 years due to the climate warming (Palagushkina, Nazarova & Frolova, 2019).

Paleolimnological studies of lakes of mountain steppe of the Southern Urals are limited. The first geochemical, granulometric, and mineralogical data were published for the Holocene and Late Glacial sediment cores of Lake Bannoe (Yaktykul) and Sabakty (Yusupova & Nourgalieva, 2021; Kuzina et al., 2022; Yusupova, Nourgalieva & Kuzina, 2022; Maslennikova et al., 2023a; Yusupova et al., 2023). The comprehensive study including diatom, palynological, and geochemical sediment cores was carried out for Lake Talkas located 85 km southwest of Lake Yaktykul (Maslennikova, 2020). However, all these studies aimed to reconstruct the Holocene environmental changes, and, therefore, the upper part of the sediment cores covering the last several hundreds years did not have a high resolution.

Lake Yaktykul located in the mountain steppes of the Southern Urals is the deepest and cleanest lake in Republic of Bashkortostan. The paleolimnological study based on high resolution sediments record of the oligotrophic lake in the Urals steppe zone in order to determine the lake ecosystem response to climatic and anthropogenic factors is carried out for the first time. The first step to predicting the lake's response to the increased human impact and the climate warming is to study changes in the lake ecosystem over a period of pre-anthropogenic and anthropogenic impacts. Therefore, our study objectives included as follows: 1) to reconstruct changes in hydrochemical, morphometric, and trophic parameters of Lake Yaktykul over the past 300 years based on the multi-proxy study; 2) to determine the drivers of the lake ecosystem shifts. 3. to assess the consistency between the chronological boundaries and the ecosystem response to various impacts in the deep and shallow parts of Lake Yaktykul.

Study site

Lake Yaktykul (53°58'71.86"N, 58°62'85.17"E, 434 m a.s.l.) is located 30 km northwest of Magnitogorsk, on the Eastern Slope of the Southern Urals (Fig. 1). The present-day climate of the studied region is continental, with an annual precipitation of 387 mm yr^{-1}, an average annual temperature of +3.2 °C, an average July air temperature of +19.6 °C, and an average January air temperature of -14.6 °C (based on the 2001–2021 data from the Magnitogorsk meteorological station).

The lake is tectonic with a catchment area composed of volcanic deposits of the Mukasovskaya, Karamalatyshkaya, Ulutauskaya, and Bugodakskaya formations. Devonian volcanic deposits are composed of basaltic volcanoclastites, basalts, jasper, and siliceous siltstones. Bedrocks to the north of the lake are overlain by Holocene deposits as pebbles, sands, and clays (Knyazev & Kyazeva, 2008). The lake is a drainage type, and the Yangelka River flows from it. Long-term fluctuations in water level reach 1.4 m. A vegetation of the catchment area is represented by birch forests, open pine and larch forests. Steppe communities are common in the rocky areas; in the east, sparse birch forests pass into the Trans-Ural steppe (Gareev, 2005).

The human impact on Lake Yaktykul, as well as on other lakes in the Ural mining region, is related to the development of the mining and metallurgical industries in the Urals. Until 1740, the Southern Urals was developed by Russian people mainly by means of agricultural works. The active construction of metallurgical plants began from the middle of the eighteenth century. Charcoal from local forests was used as a fuel. After the Pugachev’s Rebellion (AD 1773-1775), when almost all plants in the Southern Urals were burnt, and the AD 1776 Decree having prohibited the construction of new factories, the metallurgy development slowed down (Svistunov, 2019). Many plants continued to operate, but there was no such industrial growth as in the mid-eighteenth century. Many plants were closed after AD 1861 AD. A new period of industrial activity begun in the twentieth century was interrupted by the October Revolution in AD 1917. Many plants started working again after AD 1925. The largest industrial growth in the Urals occurred following the industrialization (AD 1928–1941) and the World War II (AD 1939–1945). A reduction in industry was observed in the 1990s. The new growth of industry began only at the beginning of the twenty-first century (Alekseev, 2001).

Until the beginning of the twentieth century, the direct anthropogenic impact on Lake Yaktykul was related to the livestock grazing in the catchment area. Forest cutting was started in this area in the 1920s. In AD 1916, the first manganese ore batch was obtained in the Kusimovsky Mine. The mine has been developed by open-pit mining since AD 1930 and by shaft mining since AD 1935. In AD 1930, the city of Magnitogorsk was founded at the site of the Magnitnaya Settlement (founded in AD 1743), at a distance of 40 km from the lake, due to the construction of the Magnitogorsk Iron and Steel Works. In AD 1930, small settlements were built near the lake (Kuskil’din, 2007). The forest cutting, operation of the Kusimovsky Mine and the Magnitogorsk Plant became more active during the World War II (AD 1939-1945). In AD 1957, the Kusimovsky Mine stopped its operation ((Alekseev, 2001; Kuskil’din, 2007). The Magnitogorsk Iron and Steel Works has continued to work to date.

The population of small settlements varied on the Lake Yaktykul shore, reaching the maximum in the middle of the twentieth century (1,721 people) and then gradually decreased (Kuskil’din, 2007). At the beginning of the twentieth century, the number of residents ranged from 2,500 to 10,000 in Magnitogorsk. Since the 1930s, the number of residents grew rapidly, having reached almost 150,000 in AD 1939 and more than 275,000 in 1950. After reaching the maximum in 1989 (440,000), the population declined until AD 2010 (408,000), and then began to grow again, currently reaching 420,000.

The recreational use of the study area began in AD 1932, when a seasonal pioneer camp was opened on the Lake Yaktykul shore. The first capital buildings date back to AD 1941, when health resort buildings for the Magnitogorsk Iron and Steel Works workers were finally constructed. Since the mid-twentieth century, more and more recreation centers were built on the lake shore. In 2003, a ski center was built on the lake shore. It is visited by a few hundreds of thousands tourists annually. With improving the financial well-being of the population since the beginning of the twenty-first century, the flow of tourists to the lake shores has increased. Along with large sanatoriums and recreation centers (Yaktykul, Yubileiny, Berezki, and Rodina), the number of small recreation centers and guest houses continues to increase on the lake shore, and the anthropogenic load related to a “wild” tourism is growing. Obvious sources of load on the lake include a higher terrigenous drift due to housing development on the lake shores, discharge of waste and sewage water into the lake, garbage dumps on the shore, and livestock grazing. From the 1980s until 2015, the lake’s flow was regulated by an embankment road.

2. Methods

2.1. Field methods

The sediment cores were collected with a Stratometer C1 from Lake Yaktykul at 14.5 m (BK1, BK2) and 24.5 m (BK3, BK4) water depth (Fig. 1, Table 1). The core sections were extruded and sliced in the field. BK1 and BK3 were taken mainly for diatom analysis, BK2 and BK4 were taken for analysis requiring a higher sample weight (e.g., chironomid and ^{210}Pb analysis). A sampling interval was about 1.2 cm for BK2 and BK4 and about 0.6 cm for BK1 and BK3. Water samples were collected by hand below the surface (0.3-0.5 m depth) in May, August, and October of 2021 and in August of 2022 and 2023. Samples of a bottom water were collected in August 2023. Lake depth was determined with a hand-held acoustic depth meter. Electrical conductivity was measured using a hand-held Hanna HI9333000, and pH was determined with an Aqua TROLL pH sensor. Oxygen saturation and content were measured with application of hand-held Hanna HI 9146 N. All samples were stored in plastic bags at 4°C in the dark.

2.2. Chronology

The nonequilibrium ^{210}Pb method was used to estimate a current sedimentation velocity and an age of individual horizons in the sediments of Lake Yaktykul (Kuptsov, 1986). This method is based on determining the relationship between a decline in ^{210}Pb isotope not supported by radioactive equilibrium and a depth. In general, this exponential relationship makes it possible to determine age characteristics of the lake sediments core under the radioactive decay law based on the known lead-210 half-life time (22.2 years). The ^{210}Pb content in individual layers of the core was determined in terms of the specific alpha activity of its daughter isotope ^{210}Po extracted from the samples by complete dissolution of the lake sediments sample, followed by the selective separation of polonium from the solution on a nickel disk(Ampelogova, 1976; Grigoriev, 2016). The alpha spectrometric measurements of ^{210}Po analytical preparations were carried out by means of an ORTEC Alpha-Duo spectrometer with an ion-implanted silicon detector in the Laboratory for Geomorphological and Paleogeographic Studies of the Polar Regions and the World Ocean at the St. Petersburg State University.

2.3. Laboratory analysis of water

Chemical analysis of water was carried out in the Laboratory of South Urals Research Center of Mineralogy and Geoecology, Ural Branch, Russian Academy of Sciences (SU FRC MG UB RAS), in accordance with traditional hydrochemical analysis methods (Murav’ev, 2011). Analysed variables included anion and cation concentrations, color, permanganate value (PV), total phosphorus (TP), and total nitrogen (TN) (Table 2). Anions and cations were measured in water filtered through a 0.45-μm cellulose-acetate filter. Salinity was calculated as the sum of dissolved ions as mg l^{-1}. Concentrations of carbonates and bicarbonates were determined by potentiometric titration; chlorides, by argentometric titrimetry; and sulphate ions, by gravimetric method. Concentrations of nitrate, nitrite, ammonia, and phosphates were determined by photometry. An atomic absorption spectrometer (Perkin Elmer 3110, the USA) was used to determine Ca and Mg (in acetylene-air mode), Na and K (in flame-emission mode). A water color was determined visually using a chrome-cobalt scale. The PV determination included oxidation of organic and inorganic substances with potassium permanganate in sulfuric acid and subsequent addition of oxalate ion and titration. Total phosphorus was determined in unfiltered lake water by acid persulfate digestion and spectrophotometry. Chlorophyll-a (Chl-a) was measured in surface water by spectrophotometry (Spectrophotometer SF-56) after filtration and extraction into ethanol. Total nitrogen was determined using a Topaz NC analyser. The Topaz NC operation principle is based on high-temperature thermal catalytic oxidation of nitrogen contained in a water sample, followed by detection of element oxides and calculation of the initial content of all forms of N compounds in the sample. Trace element concentrations in the lake water were determined by inductively coupled plasma-source mass spectrometry (ICP–MS) using Agilent 7700 (Supplementary Table S1).

2.4. Laboratory analysis of sediments, algae, submerged vegetation, catchment soils, rocks, and gravel

Trace element concentrations in the lake sediments, coastal soils, rocks, and gravel were determined by ICP–MS with Agilent 7700 in the SU FRC MG UB RAS. The method was described in detail in (Maslennikova et al., 2020).

The isotopic composition of organic carbon was determined in the SU FRC MG UB RAS with a DeltaPlus Advantage mass spectrometer (Thermo Finnigan) coupled with a ConFlo III interface with an EA Flash1112 elemental analyzer. The quantitative data were obtained by processing the mass spectra with the help of a computer using a special software. The results were reported as the quantitative data (0.00 ‰, VPDB). The NBS19 standard was used in the studies. The device measurement error when determining the carbon composition was 0.09 ‰. Samples meant for the δ^{13}C analysis were collected mainly from Lake Yaktykul and its catchment. Leaves of *Betula pendula* Roth. and *Pinus sylvestris* L., widespread in the Lake Yaktykul catchment, were collected from other Southern Urals areas (Supplementary Table S2).

Carbon and nitrogen contents in organic matter of lake sediments were determined by the dry combustion method with a Vario Isotope Cube CHNS analyzer (Elementar, Germany) at the Center for Collective Use “Laboratory of Radiocarbon Dating and Electron Microscopy”, Institute of Geography, Russian Academy of Sciences.

2.5. Palynological analysis

For the purpose of the palynological analysis, samples were prepared from 0.25 g of sediment sample using standard KOH and HF techniques (Faegri & Iversen, 1989). The prepared samples were placed in glyceryne for identification. Counts of at least 300 pollen grains of terrestrial plants per sample were used to calculate percentages. Each sample was counted under a light microscope at 400X magnification. Beside pollen and plant spores, non-pollen palynomorphs (NPP) and microcharcoal particles (10-150 µm) were counted. Microcharcoals and non-pollen palynomorphs were expressed in % to the total of pollen and spores. NPPs were identified with the help of the Non-Pollen Palynomorph Image Database (http://nonpollenpalynomorphs.tsu.ru/) (Shumilovskikh et al., 2022). Plant pollen and spores, NPP, and microcharcoals were expressed as percentages of the total terrestrial pollen. The pollen and spore absolute concentrations (mln pollen grains and spores in 1 g of a dry weight) were calculated according to (Davydova, 1985).

2.6. Chironomid analysis

The treatment of sediment samples meant for the chironomid analysis followed the standard techniques (Brooks, Langdon & Heiri, 2007). Subsamples of wet sediments were deflocculated in 10% KOH, heated to 70°C for 10 min by adding boiling water, and left for another 20 min. The sediment was passed through stacked 225 and 90 µm sieves. Chironomid larval head capsules were mounted in Hydromatrix under a 6 mm diameter cover slip. Chironomids were identified to the highest taxonomic resolution possible with reference to Wiederholm (Wiederholm, 1983) and Brooks et al. (Brooks, Langdon & Heiri, 2007). The data on chironomid taxa ecology were taken from different sources (Brooks, Langdon & Heiri, 2007; Nazarova et al., 2008, 2011, 2015, 2017a, 2017b, 2023; Moller Pillot, 2009, 2013).

The effective numbers of chironomid taxa were estimated using the Hill`s N2 index (Hill, 1973). The Principal Component Analysis (PCA) was used to explore the major taxonomic variation patterns and to compare them within the chironomid data throughout the sediment core (ter Braak & Prentice, 1988; Syrykh et al., 2017). Percentage stratigraphic diagrams were made in Tilia Graph. The Chironomid data were graded on the basis of weighted average of the taxa (Nazarova et al., 2020, 2021b).

2.7. Diatom analysis

For the purpose of the diatom analysis, samples were treated with nitric and perchloric acids to remove organic matter. Slides were mounted with a Naphrax mountant. A Mikmed 6 var. 7 microscope with bright-field oil immersion optics at 1000× magnification was used for counting. The measurements for taxonomic identification were made using the ToupView 3.7 software, and photomicrographs were obtained with a ToupCAM UCMOS14000KPA digital camera. At least 300 valves were counted per sample (diatom total) to determine a relative abundance (percentage) of individual taxa in the assemblages. The diatom identification was based on different sources

((Krammer & Lange-Bertalot, 1986, 1988, 1991a, 1991b; Kulikovskiy et al., 2016; Lange-Bertalot et al., 2017; Reichardt, 2018a, 2018b). The diatom nomenclature was updated using the online Algaebase catalogue (Guiry & Guiry, 2023). Ecological groups in relation to pH, saprobity, trophicity, and salinity were identified according to (Van Dam, Mertens & Sinkeldam, 1994). Benthic, plankto-bentic, and planktonic diatoms were distinguished in terms of a habitat (Barinova, Medvedeva & Anissimova, 2006). The diatom zonation schemes were developed with a stratigraphically constrained cluster analysis based on the log-transformed data, with a chord distance measure, using CONISS (Constrained Incremental Sums of Squares cluster analysis) in the Tilia software package (Grimm, 1991). Diagrams were constructed using the C2 software (Juggins, 2007).

2.8. Modern lake trophic state and nutrients enrichment assessment

The trophic state index (TSI) was used to assess the current trophic state of lakes based on the hydrochemical data. Total phosphorus as well as Secchi disk depth, total nitrogen, and chlorophyll-a were used as trophic state indicators. A value of $\mathrm{TSI} < 40$ is indicative of oligotrophic conditions, with mesotrophic from 40 to 50, eutrophic from 50 to 70, and hypertrophic at > 70. TSI values were calculated by the special formulae (Carlson, 1977; Kratzer & Brezonik, 1981). To determine the biogenic element that was limiting for the phytoplankton development, the following relationships were used (Matthews, Hilles & Pelletier, 2002):

Phosphorus limitation occurs if:

$\mathrm{TSI\ (Chl)} - \mathrm{TSI\ (TP)} > 0$ and $\mathrm{TSI\ (TN)} > \mathrm{TSI\ (TP)}$

Nitrogen limitation occurs if:

$\mathrm{TSI\ (Chl)} - \mathrm{TSI\ (TN)} > 0$ and $\mathrm{TSI\ (TN)} < \mathrm{TSI\ (TP)}$

2.9. Evaluation of the lake contamination in potential toxic elements

The water contamination was assessed based on the Criterion Cumulative Unit (CCU) (Clements et al., 2000) defined as:

$$CCU = \frac{Concentration\ of\ pollutant}{Criterion\ value\ for\ pollutant}$$

The pollutant criterion values represent the statutory fisheries water quality standards in force in the Russian Federation (‘Normativy katchestva, 2016 with changes in 2018 and 2020’). The criterion values for drinking water and water meant for domestic-recreation purposes in relation to U, Bi, Sb, Cd, and Tl were applied (‘Predel’no dopustimye koncentracii’, 2008) (Supplementary Table S1).

The lake sediment contamination by potentially toxic elements was evaluated with the help of the enrichment factor (EF) calculated using the following formula:

$EF = \left| Xs/Es \right| / \left| Xr/Er \right|$, where (Xs/Es) is the ratio of the element of interest (X) to the reference element (E) for the studied samples, and (Xr/Er) is the ratio of the element of interest to the reference element for the reference sediments. We used La, Zr, Hf, Nb, and Th as the reference elements. Then, the average enrichment factors were accounted. To date the beginning of PTEs accumulation, the sediments accumulated until the first smelter was built in the Southern Urals (1746 AD) were used as the reference. To assess the role of in-lake processes in the PTEs accumulation, we applied soils, rocks, and gravel on the coast as the reference. The enrichment index (EI) was calculated by analogy with the pollution load index (PLI) (Tomlinson et al., 1980) to compare a PTE enrichment degree in sediments of Lake Yaktykul and other Urals lakes (Maslennikova et al., 2023b). Instead of the contamination factor, we used the enrichment factor in the formula to consider a terrigenous dilution of sediments:

$$\mathrm{EI} = \sqrt[n]{\mathrm{EF1} \times \mathrm{EF2} \ldots \times \mathrm{EFn}}$$

2.10. Application of trace elements in paleoreconstructions

The terrigenous component content in lake sediments can increase with fluctuations in the water reservoir level and more severe erosion of the catchment area. The terrigenous component content (%) was determined by the formula (Leonova & Bobrov, 2012):

$Terr.comp. = \frac{Xs \times 100}{Xr}$, where Xs is a terrigenous element concentration in sample, and Xr is a terrigenous element concentration in clay shale according to (Yuan-Hui, 1991). Calculations are based on the assumption that the ash content of clay shale is 100%. La, Th, Zr, Hf, and Nb were used as terrigenous samples. For the interpretation purposes, we applied average % of a terrigenous component.

Li and Sr concentrations were used to perform quantitative reconstructions of water EC variations in Lake Yaktykul using a multiple regression model previously obtained based on the geochemical data on 107 lakes in the Urals (Maslennikova et al., 2023a):

$$lgEC = 0.73\,Li + 0.77\,Sr$$

Due to the fact that Sr, Ca, and calcite contents were very highly correlated in lake sediments of the studied lakes in the Urals (Maslennikova et al., 2023a), the Sr concentration was also used to assess the calcium carbonate accumulation in the lake.

Application of organic carbon (C), nitrogen (N), C/N, and $\delta^{13}C$ in paleoreconstructions

Organic carbon and nitrogen contents, C/N, and $\delta^{13}C$ can be indicative of the lake ecosystem productivity, with regard to an organic matter decomposition velocity and a potential for sediment diluting by autochthonous or allochthonous inorganic matter (Meyers, 1994). In addition, the organic carbon-to-total nitrogen ratio (C/N) is used to determine an organic matter source. The following conclusions are common to the C/N studies of various plants (Stuiver, 1975;

Krishnamurthy, Bhattacharya & Kusumgar, 1986; Meyers & Benson, 1988; Meyers & Teranes, 2002; Lamb et al., 2004; Burgess, 2007; Thevenon et al., 2012):

1. C/N of algae is commonly less than 10;
2. C/N of terrestrial vascular plants is commonly more than 20;
3. C/N of aquatic vascular plants is intermediate between algae and terrestrial vascular plants.

The carbon isotopic composition of lake sediments is also highly dependent on the isotopic composition of organic matter sources. To provide a correct interpretation of the carbon isotope analysis data on lake sediments of Lake Yaktykul, we studied the carbon isotope composition of potential organic matter sources. We carried out the $\delta^{13}C$ analysis of terrestrial substrates (11 samples), terrestrial plants being common in the catchment area (11 species), aquatic vascular plants (11 species), and algae (*Spirogyra* sp., *Charophyceae*, and Bacillariophyta) (Supplementary Table S2) collected in Lake Yaktykul.

2.11. Chironomid-based climate reconstructions

To reconstruct the mean July air temperature (T July), the North Russian (NR) we applied a chironomid–based temperature calibration training set which included the data from 193 lakes (Nazarova et al., 2015). The modern T July for the lakes from the calibration dataset were derived from New et al. (2002). The chironomid-inferred T July were corrected to 0 m a.s.l. using a modern July air temperature lapse rate of 6 °C km^{-1} (Livingstone, Lotter & Walker, 1999; Renssen et al., 2009; Heiri et al., 2014; Rudaya et al., 2021). The two-component weighted average – partial least square (WA-PLS) Northern Russia model (NR) – has a determination factor $r_{jack}^2 = 0.87$ and a standard error of prediction (RMSEP) = 1.35 °C. A water depth (WD) was reconstructed using a modern chironomid-based calibration data set (Nazarova et al., 2011) which included 147 lakes. The one-component WA-PLS model had the best performance: $r_{boot}^2 = 0.62$ and RMSEP = 0.35 m. Both inference models were previously applied for palaeoclimatic inferences across Eurasia demonstrating a high reliability of reconstructed parameters (Wetterich et al., 2018; Druzhinina et al., 2020; Nazarova et al., 2021a, 2023). Chironomid percentage data were square-root-transformed and rare taxa were downweighted. Chironomid-based reconstructions and PCA were performed in C2 version 1.7.7 (Juggins, 2007).

The chironomid-inferred reconstruction accuracy was assessed by several methods. The percentages of the fossil chironomid taxa that were absent or rare in the modern calibration dataset were calculated (Andreev et al., 2022). A taxon was considered as rare in the modern dataset when Hill’s N2 was below 5 (Hill, 1973). The environmental optima of taxa that were rare in the modern dataset were likely to be poorly estimated (Brooks & Birks, 2001). The modern analogue technique (MAT) was performed using C2 version 1.7.7 (Juggins, 2007) with squared chord distance as the dissimilarity coefficient in order to determine whether the modern calibration models had adequate analogues for the fossil assemblages (Overpeck, Webb & Prentice, 1985; Plikk et al., 2019). Samples with dissimilarity larger than the 5th percentile threshold in the modern data are frequently considered as having no good analogues in the modern calibration dataset (Birks, Juggins & Line, 1990; Francis et al., 2006; Palagushkina et al., 2017).

2.12. Diatom-based quantitative reconstructions

The electrical conductivity reconstruction involved a transfer function developed using a 90-lake regional diatom dataset was applied (Maslennikova, 2020, 2023). For the purpose of total phosphorus reconstructions, two TP diatom datasets were applied: a combined TP diatom dataset from the European Diatom Database Initiative (EDDI) (Lotter, 1989; Bennion, 1994; Wunsam & Schmidt, 1995; Bennion et al., 1996; Bennion, Juggins & John, 1996; Rioual, 2000) and a regional Urals lakes dataset ((Maslennikova, 2023). Diatom-based inference models were developed by simple weighted averaging (WA) and weighted averaging partial least squares methods using the log-transformed species relative abundance data (ter Braak & Juggins, 1993; Birks & Birks, 1998). The performance of all transfer functions was evaluated by mean square error of prediction, as estimated by bootstrapping ($RMSEP_{boot}$) and associated model statistics such as a maximum bias and a coefficient of determination (r^2_{boot}) between predicted and observed values (Birks, Juggins & Line, 1990). EC and TP transfer functions and reconstructions were developed using the C2 software (Juggins, 2007).

For the purpose of assessment of the EC and TP reconstruction reliability, the modern analogue technique (Birks, 1998; Laird et al., 1998) was used to evaluate the similarity of modern diatom assemblages to core assemblages. The extent to which EC and TP tracked the main variation trends of the fossil diatom assemblages was assessed: a) by calculation of correlation between DI–EC and DI–TP in the core to the PCA axis-1 and -2 scores of the fossil diatom assemblage; b) by calculation of the λ_R/λ_P ratio, where λ_R is the eigenvalue of the first axis of a redundancy analysis (RDA) of the fossil diatom assemblage constrained to the diatom-inferred parameter, and λ_P is the eigenvalue of the first axis of a PCA of the same down-core diatom assemblage (Juggins, 2013; Cumming et al., 2015).

To assess the influence of different factors on the lake ecosystem, we used the historical data on industry development and local land use activity. In addition, RDAs with annual mean temperature (AMT) and mean temperatures of each month of the year as explanatory variables were applied for detection of the relationship between diatom assemblages and climatic parameters. Climatic parameters were obtained from the meteorological archives containing the data since 1832 AD (http://www.pogodaiklimat.ru/history/35023.htm). We used the temperature data on Orenburg, despite the fact that it is located further than Magnitogorsk from the studied object, due to a longer observation period (since 1832 vs 1936) and a high correlation (r>0.9) of temperatures in

Magnitogorsk and Orenburg. The correlation between precipitation variations in Magnitogorsk and Orenburg was much lower (r=0.3-0.7). For this reason, in order to assess the precipitation effect, we had to use the data from Magnitogorsk (http://www.pogodaiklimat.ru/history/28838_2.htm) located much closer to the lake. To assess whether the variable of interest explained a unique and significant fraction of variance in the diatom species assemblages, the RDA was run for each variable individually and with other significant variables as conditional covariables. All ordinations were implemented in CANOCO 4.5. (ter Braak & Smilauer, 2002). The relationship between climatic parameters, DI-TP, ecological diatom groups, ratio of diatoms to Chrysophyceae cysts, diatom diversity and uniformity were determined by the correlation analysis: Pearson correlation (r) and Spearman rank order correlation (R).

3. Results

3.1. Chronology

The ^{210}Pb activity supported by radioactive equilibrium in the ^{238}U series (^{210}Pb$_{supp}$) was estimated as a weighted average of the ^{210}Pb values determined for several lower layers of the cores. The ^{210}Pb activity was similar in these layers, despite the changing depth, due to reaching the ^{210}Pb equilibrium region. The ^{210}Pb$_{supp}$ activity reached 18.18 ± 0.36 Bq kg^{-1} for the BK2 core and 18.23 ± 0.39 Bq kg^{-1} for BK4. A good consistency of ^{210}Pb$_{supp}$ values obtained for two different cores additionally indirectly confirms our assessment of the ^{210}Pb$_{supp}$ content in Lake Yaktykul sediments. The unsupported ^{210}Pb activity was determined by subtracting the supported activity from the total activity. The ^{210}Pb$_{ex}$ distribution series for BK2 and BK4 are well-approximated by exponential relationships due to an approximate constancy of sedimentation velocity over the last ~150 years. Hence, it is possible to apply the constant initial concentration model (Kuptsov, 1986) to calculate an average sedimentation velocity at the sampling sites of BK2 (shallow-water part) and BK4 (deep-water part) cores.

1) BK2: 0.95 ± 0.04 mm/yr for 122.9 ± 5.2 years for upper 12.8 cm;

2) BK4: 0.99 ± 0.03 mm/yr for 152.2 ± 4.9 years for upper 17.5 cm.

The consistent variations in ^{210}Pb$_{ex}$ in BK4 also make it possible to apply the constant rate of supply model (CRS) (Kuptsov, 1986) to estimate the age of its individual layers without taking into account a sedimentation velocity which can vary under this model. Comparison of these values with those derived from an average sedimentation velocity under the constant initial concentration (CIC) model does not reveal considerable differences, except for the area beyond the lead-210 dating method. This fact can be indicative of a uniform sedimentation in Lake Yaktykul for the last ~150 years.

3.2. Chemical analysis of lake water

According to the hydrochemical analysis (Table 2), Lake Yaktykul is freshwater, calcium bicarbonate-dominated with magnesium as the sub-dominant cation. Based on trophic state indices calculated from average TP, TN, and SD, Lake Yaktykul is oligotrophic. Water sampled in August 2023 differed in slightly lower TP, substantially lower TN, and higher SD (Table 3). According to TSI(TN) in deep-water sampling site, the lake was ultraoligotrophic in August 2023. The calculations carried out using special formulas (Matthews, Hilles & Pelletier, 2002) yielded the nitrogen limitation in August 2023. Meanwhile, in previous years, TSI_{TN} was always higher than TSI_{TP}.

According to the measurements carried out in August 2023 (Table 3), surface water is saturated by oxygen (98-110%). Oxygen saturation and content decrease with depth. In upper 10 m of water column, oxygen percentage and content slowly decrease from 98-110% (8.0-8.9 ppm) to 86-89% (7.8-7.9 ppm). At the depth interval of 10-15 m, its content decreases very rapidly to 3.2-4.5 ppm (30-46%). At the depth of 18 m, the oxygen content is 1.6 ppm (15-16%), and from the depth of 20 m, 0.3-0.8 ppm (3.5-7%). Contents of phosphate phosphorus and total phosphorus in the bottom water were three times higher than in the surface water.

According to the ICP-MS results obtained for water sampled in May, August, and October 2021, none of potential toxic elements exceed the criterion value for fishery reservoirs (‘Normativy katchestva, 2016 with changes in 2018 and 2020’). (Supplementary Table S2).

3.3. Geochemistry of lake sediments

3.3.1. Evaluation of the lake sediments contamination in potential toxic elements

Based on the comparison of industrial and pre-industrial period, sediments accumulated since the 1930s were enriched in Zn (EF=1.4-1.7), Cd (EF=1.2-2.9), Sn (EF=1.2-3.0), W (EF=2.0-5.2), Pb (EF=1.6-5.0), Tl (EF=1.4-1.8), As (EF=1.8-3), and Bi (EF=2.9-16.4). Enrichment indices of industrial sediments did not exceed 3.4. Comparison between trace-element concentrations in lake sediments and catchment rocks, soils, and coastal gravel made it possible to reveal that sediments were enriched in Mo (EF=13-53), Cs (EF=2.6-3.4), Sn (EF=2.5-10), V (EF=2.1-2.5), W (EF=1.2-3.9), Sb (EF=1.5-6.4), and Bi (1.8-29). Enrichment in Sn, Sb, Bi, W, as well as Zn, Cd, Pb, Tl, and As increased in sediments accumulated since the 1930s. Sediments enriched in Sr and Ba (EFs=1.5-2.2) accumulated in the period between AD 1907 and AD 1970. Enrichment index slightly increased at AD 1840-1850 and began quickly increase since the 1930s. The maximum EI was noted for sediments of AD 1983-1996. Then, the enrichment of sediments in PTEs stopped, and EI remained almost the same (no more than 3.5). Concentrations of trace elements in sediments are represented in Supplementary Table S3.

3.3.2. Carbon isotope composition of organic matter sources in Lake Yaktykul

The study of isotope composition of organic carbon of aquatic plants, terrestrial plants, and different terrestrial substrates made it possible to draw several conclusions.

1. The lightest isotope composition was characteristic for organic carbon of terrestrial substrates (average - 27‰, median - 29‰). Minimum values (- 36‰) were observed for coastal gravel of silicites and volcanoclastic basalt rocks. Maximum $\delta^{13}C$ (- 26‰) was calculated for soils located in different points by the lake shore (Supplementary Table S2).

2. Terrestrial plants are characterized by a slightly heavier organic carbon isotope composition (average and median - 27‰), with the lightest $\delta^{13}C$ for *Ulmus pumila* L. (- 28.4 ‰) and the heaviest $\delta^{13}C$ for *Larix sibirica* Ledeb. (26.4 ‰).

3. Aquatic vascular plants $\delta^{13}C$ was heavier (- 16 ‰ in average and - 14 ‰ in median). Its isotope composition was partially dependent on a growth form (according to Clarke, 2012). Isotope composition of emergent plants varied substantially with the lightest $\delta^{13}C$ for *Thelypteris palustris* Schott. (- 29 ‰) and the heaviest $\delta^{13}C$ for *Sagittaria sagitifolia* L. (- 17.5 ‰) from which mainly underwater leaves and stems were sampled. Leaves of floating-leaved plants (*Nuphar pumila* (Timm) DC.) were characterized by a relatively light isotope composition (- 24.6 ‰). The minimum obtained for free-floating plants was marked for *Lemna trisulca* L. (- 14‰) and the maximum, for *Ceratophillum demersum* L. (- 11‰). Isotope composition of submerged plants varied between -16.4 ‰ for *Potamogeton trichoides* Cham.& Schltdl. and 8.3 ‰ for *Stratiotes aloides* L.

4. Algae organic carbon isotope composition varied between - 14 ‰ (for *Charophyceae*) and -17 ‰ (for epiphytic diatoms and *Spyrogira* sp.)

3.3.3. Geochemical record (BK4, lake sediments core of the deep-water part)

Contents of organic carbon and total nitrogen in the studied sediments of Lake Yaktykul are 11.6-29% and 1.1-3.4%, respectively (Fig. 2). C/N ratio varies along the vertical profile from 8.0 to 12, while $\delta^{13}C$ is -24‰...-26‰. The terrigenous component varies from 10.5 to 23%. Sr varies slightly (88-110 µg kg-1) during almost the entire period of lake development we studied, except for the period between AD 1911 and 1972 (159-218 µg kg^{-1}). According to the water salinity classification based on electrical conductivity ranges (Stewart & Kantrud, 1971) and our quantitative reconstructions of electrical conductivity, the lake has remained freshwater for the last 300 years. Electrical conductivity reconstructed using multiple regression model (GI-EC) varies between 180 and 320 µSm cm^{-1}.

Four geochemical zones (GZI-IV) were distinguished based on the geochemical data:

GZI (AD 1720-1781). The lake is characterized by G-I EC of 180-210 µSm cm^{-1}, a terrigenous component is no more than 13%, and $\delta^{13}C$ is variable (-24.6...-25 ‰). Sr is the lowest (88-101 µg kg^{-1}).

GZII (AD 1781-1844). Geochemically inferred electric conductivity (207-223 µSm/cm), terrigenous component (13-16%), and Sr (94-108 µg kg^{-1}) increase, while δ^{13}C ranges within - 24...-25 ‰. Organic carbon, nitrogen, and C/N vary between 13.6 and 15%, 1.4 and 1.6%, and 8.9 and 9.5, respectively.

GZIII (AD 1844-1911) is marked by a decrease in G-I EC (181-210 µSm cm^{-1}), terrigenous component (11-13%) and an increase in organic carbon (15.6-17.8%), nitrogen (1.7-2%) and slight enrichment in potential toxic elements (EI of 1.3-1.6).

GZIV (AD 1911-1972) is characterized by a considerable increase in GI-EC (246-320 µSm cm^{-1}), Sr (150-218 µg kg^{-1}), δ^{13}C, and C/N (9.4-11.9) (Fig. 2). Terrigenous component, organic nitrogen and carbon decreased. Since the second half of the twentieth century, GI-EC, Sr, δ^{13}C, and C/N decreased, whereas terrigenous component and organic nitrogen increased. Enrichment of sediments in Zn, As, Sb, W, Bi, and Pb increased since the 1930s.

GZV (AD 1972-2021) is marked by an ongoing decrease in water conductivity and low Sr (100-110 µg kg^{-1}). C/N is the lowest and varies between 8 and 8.8, while a terrigenous component is the highest (21-23%). Enrichment index increases due to Sn, Cd, Sb, Pb, Tl, and Bi until the 1990s and then remains constant.

3.4. Palynological record (BK2, lake sediments core of the shallow-water part)

Arboreal pollen prevailing in Lake Yaktykul sediments is represented mainly by *Pinus sylvestris L.* and *Betula sect. Albae*. Contents of *Picea* sp., *Larix sibirica* Ledeb., *Alnus spp.* +*Alnaster* spp., and broad-leaved trees pollen (*Querqus* sp., *Ulmus* sp., *Tilia* sp.) do not exceed 5%. Only several pollen grains of *Abies sibirica* Ledeb. and *Salix* spp. were observed. We found an anther with pollen of a larch in the sample BK2/19 (21-22 cm, AD 1792-1804). This fact, as well as a good larch pollen preservation in lake sediments, point to trees in the watershed and near the lake. Pine and birch pollen characterized by a different preservation are related to long-distance and local pollen sources. Pine pollen increased twice: in the middle of the nineteenth century simultaneously with a non-arboreal pollen decrease and in the first half of the twentieth century simultaneously with a birch pollen decrease (Fig. 3).

Non-arboreal pollen is dominated by *Artemisia* spp. and subdominated by other anemophilous herbs (Amaranthaceae and Poaceae). Several pollen grains of Apiaceae and Asteraceae were observed. Spores represented by monolete bilateral spores of Polypodiaceae and several spores of *Sphagnum* spp. do not exceed 2%. Mololete spores with perisporium belong to *Thelypteris palustris* Schott. which often grows near the Lake Yaktykul shore. Palynomorphs of emergent plants included pollen of Cyperaceae, *Typha* spp. and spores of *Thelypteris palustris*. Pollen of aquatic vascular plants (*Stratiotes aloides* L., *Myriophyllum spicatum* L.) was found only in sediments accumulated in the middle of the twentieth century (approximately AD 1937-1975).

Botryococcus spp. colonies and globose microfossil HdV-128 (https://non-pollen-palynomorphs.uni-goettingen.de/detail_type.html?Id=HdV-128) both increased since the second part of the nineteenth century and changed dramatically in the 1980s: HdV-128 increased and *Botryococcus* spp. decreased since 1970-1980 AD.

Fungi are negligible in lake sediments (0-8.4% of the terrestrial pollen total). Contents of Fungi spores were minimum in the middle of the twentieth century and maximum since 1980s. Despite small amounts, fungi are relatively diverse in the Lake Yaktykul sediments. We found fungi which could grow on a dung (*Gelasinospora* sp., *Sporormiella* sp., *Delitschia* sp.), as well as the species growing on a submerged wood (MM-291, *Delitschia* sp.). The number of spores which could induce the soil erosion (UAB3, Uka-6 - aff. *Boletus*) increased, and ascospores HdV-3a and NN-157 appeared since AD 1970-1980. Microcharcoal particles increased since the beginning of the twentieth century (Fig. 3).

3.5. Chironomid analysis

3.5.1. Reliability of chironomid-based reconstructions

All chironomid taxa that appear in the fossil record at least once under abundance of ≥ 2% are well-represented (N2> 5) in the modern NR training set. According to the MAT diagnostics data, chironomid communities have mainly good or fair analogues in the T July training set (Fig. 4). However, four samples (1, 3.75, 12.5, and 25 cm) show poor analogues with the training set. Two chironomid taxa having N2 ≥5 in the fossil record are underrepresented in the WD training set: *Cladopelma lateralis*-type (N2= 5.8) and *Paratanytarsus* (N2=10.5). Based on the MAT diagnostics of the WD reconstruction, several samples have poor analogues with the training set: 3.75, 10, 25, and 30 cm. Other samples have good or fair analogues.

The high representation of the chironomid taxa in the training sets, together with mostly good or fair MAT results, are indicative of the fact that the chironomid-based reconstructions from the investigated core are reliable. However, the reconstructions at the depths with poor analogues should be considered with caution.

3.5.2. Description of chironomid analysis results

In total, we identified 42 chironomid taxa in BK-4 lake sediments core (deep-water part). Evenness indices are high, ranging from 0.7 to 0.9 (median=0.8). They record a high stability of the communities and the absence of clear dominants. *Cladotanytarsus mancus*-type was found in all investigated horizons. This taxon is typical for a littoral of warm, productive lakes. Phytophilic taxa such as *Psectrocladius sordidellus*-type, *Dicrotendipes nervosus*-type, *Endochironomus albipennis*-type, *Cricotopus,* and *Orthocladius* taxa are well-represented in all studied zones.

The down-core variations in the chironomid assemblages led to the identification of three chironomid zones (CH I-III).

The zone CH I – (30 – 16 cm; AD 1718–1860) is dominated by *Tanytarsus pallidicornis*-type. This taxon is characteristic for a littoral of relatively productive lakes and can tolerate acidic conditions. Abundances of oligotrophic *Corynocera ambigua (Brooks, Langdon & Heiri, 2007)* that can be associated with *Chara* algae (Nazarova et al., 2013) and mesotrophic *Dicrotendipes nervosus*-type gradually increase up to 14–18% toward the sediment depth of 19 cm (ca AD 1825) and decrease then at the depth of 17 cm (ca AD 1850). At this depth, *Cladotanytarsus mancus*-type and *Tanytarsus pallidicornis*-type have the highest abundances in the core. Acidophobic *Stempellinella – Zavrelia* occurs in the lower part of the core and disappears after 26 cm (ca AD 1756). Littoral oligotrophic *Pseudochironomus* is present in almost all investigated horizons of the zone.

The diversity of chironomids decreases steadily along the zone from the highest in the core N2 = 14.8 at the depth of 27 cm (ca AD 1750) to the lowest in the core (N2 = 8.7) at the depth of 17 cm (ca AD 1850).

The reconstructed temperature fluctuates (16.0 ±0.6 °C) slightly below modern mean T July up to 19 cm (ca AD 1825) and drops thereafter to 14°C. The water depth is 25 ± 2 m with the deepest WD of 27 m at 25 cm (ca AD 1768).

Zone CH II – (16–11 cm, AD 1860–1907). *T. pallidicornis*-type, the most abundant in the previous zone, disappears in the beginning of this zone and occurs toward the upper part (at 12 cm, ca AD 1900). Cold stenothermic taxa *Corynocera ambigua*, *Tanytarsus lugens*-type, and *Parakiefferiella triquetra*-type are characterized by the highest abundances at 15 cm (ca AD 1869).

The N2 diversity remains relatively low within this zone (N2 = 9.9 ±0.6).

The reconstructed temperature remains low (14.2 °C) at the beginning of the zone and increases towards the end of the zone (to 15.2 °C). At the 15 cm sediment depth (ca AD 1869), the reconstructed WD is the deepest (29 m), and it drops to 25 m at the 12 cm depth (ca AD 1900).

Zone CH III – (11 – 0 cm, AD 1907–2021). A considerable taxonomic shift recorded by the PCA 1 is observed after AD 1907 (11 cm). The ubiquistic sublittoral *Microtendipes pedellus*-type and profundal *Chironomus anthracinus*-type are predominant in the chironomid communities. The *T. pallidicornis*-type is present in all horizons of the zone at a median abundance of 9%. The abundance of littoral *Pseudochironomus* increases along the zone from 0 to the highest in the core 15% at the depth of 1.25-2.5 cm (ca AD 1996-2008). Semiterrestrial *Limnophyes – Paralimnophyes* and *Pseudosmittia* occur in the upper part of the zone (AD 1945-1958, AD 1983-1996).

The N2 diversity of chironomid communities grows from 9.2 (10 cm; ca AD 1920) to 14.4 (3.75 cm; ca AD 1983) and constitutes 12.3 ± 1.7, on average.

The reconstructed temperature starts to grow after 3.75 cm (ca AD 1983) and reaches 17.9°C at the upper investigated sediment depth. This value is very close to the modern observed 10-year average T July (17.27 °C; http://www.pogodaiklimat.ru/history/28838.htm). The reconstructed water depth fluctuates around 21.8 ± 1.9 m which is slightly below the modern level.

3.6. Diatom analysis

3.6.1. Assessment of transfer functions and reliability of reconstructions of DI–EC and DI–TP

WA with classical deshrinking ($RMSEP_{boot}$=0.2 log10 µS cm^{-1}, bootstrap r^2=0.8, maximum bootstrap bias=0.2 log10 µS cm^{-1}) was the best-performing model for EC. WA-PLS-Component 2 was the most efficient model for TP based on both the combined EDDI dataset and the Urals lakes dataset. The bootstrap r^2 and $RMSEP_{boot}$ for the transfer function developed based on the EDDI combined dataset were higher (0.75 and 0.3 log10 µg L^{-1}) than those for the transfer function developed using the Urals lakes dataset (0.64 and 0.2 log10 µg L^{-1}) (Maslennikova, 2023). Maximum bootstrap bias for the EDDI transfer function and for the Urals transfer function was the same (0.4 µg L^{-1}).

TP reconstructed by EDDI and Urals transfer function did not correlate. According to the modern analogue technique, fossil samples of both cores had good analogue samples only in the Urals lakes calibration dataset. The values of EC and TP inferred from diatoms in the Lake Yaktykul surface sediment samples based on regional transfer function were slightly overestimated compared with the measured values (14-15 µg L^{-1} vs 9-10 µg L^{-1} and 208-211 µS cm^{-1} vs 167-202 µS cm^{-1}). TP inferred with application of the EDDI transfer function was substantially higher than the real value (30-37 µg L^{-1} vs 9-10 µg L^{-1}). Thus, we decided to apply only the regional transfer function for quantitative reconstructions.

In relation to BK3, the diatom-based TP reconstruction correlated to PCA-axis-1 scores (r=0.6) only for the part accumulated between 1826 and 1992 AD (λ_R/λ_P = 0.4). The diatom-based EC reconstruction correlated to PCA axis-2 scores (r=0.65) with λ_R/λ_P of only 0.17. In the period between 1790 and 1907, the correlation with PCA axis-2 scores increased (r=0.74), and λ_R/λ_P was 0.65. Given that λ_R/λ_P was less than one, we supposed that other variables could influence diatom assemblages (Juggins, 2013).

In relation to BK1, DI–TP correlated to PCA axis-1 scores (r=-0.5) and showed a λ_R/λ_P ratio of 0.56. For the period between 1797 AD and 1967 AD, the correlation with PCA axis-1 was stronger (r=-0.7), and λ_R/λ_P was higher (0.7). DI–EC was not a significant variable.

3.6.2. Diatom record of BK3 sediments core (deep-water part)

144 diatom species and varieties were identified by diatom analysis of the Lake Yaktykul sediment core. In terms of habitat, diatoms are represented mainly by planktonic (up to 71%) and plankto-benthic (up to 64%) species. However, benthic diatoms in lake sediments are the most diverse. In total, 109 benthic, 14 plankto-benthic, and 12 planktonic diatom species were found in the lake sediment core. In relation to pH, most species are alkaliphiles; in terms of saprobity,

oligosaprobes and β-mesosaprobes; in terms of trophic status, meso-eutrophic and indifferent; and in terms of mineralization, oligohalobes. The Shannon diversity index varies from 2.1 to 2.9, and the Shannon evenness index varies from 0.6 to 0.8. DI-TP varies from 14 to 21 μg L^{-1}. The minimum value is typical for DI-TP of AD 2015-2021, and the maximum value is obtained for DI-TP of AD 1990-1996. Chrysophyceae cysts vary between 1.5 and 11.5 mln g^{-1} in dry weight.

Five diatom zones were identified by stratigraphically constrained cluster analysis (Fig. 5): DZI (AD 1789-1841) is dominated by planktonic species represented mainly by *Aulacoseira ambigua* (Grunow) Simonsen 1979 and, to a much lesser extent, by *Pantocsekiella comensis* (Grunow) K.T.Kiss & E.Ács in Ács et al. 2016, *Stephanodiscus alpinus* Hustedt in Huber-Pestalozzi 1942, and by species referred by (Kulikovskiy et al., 2016) to *Handmania comta* (Ehrenberg) Kociolek & Khursevich 2012.

Plankto-benthic species are dominated by *Pseudostaurosira brevistriata* (Grunow) D.M.Williams & Round 1988 and *Staurosira venter* (Ehrenberg) Cleve & J.D.Möller 1879.

Major benthic diatom species include *Staurosirella lapponica* (Grunow) D.M.Williams & Round 1987, *S. pinnata* (Ehrenberg) D.M.Williams & Round 1988, and *Amphora indistincta* Levkov 2009; *Karayevia clevei* (Grunow) Bukhtiyarova 1999 and *Staurosira tabellaria* (W.Smith) Leuduger-Fortmorel 1878 are constant in occurrence. Diversity and evenness indices are minimum.

Chrysophyceae stomatocysts are minimum (1.5-9 mln per 1 g of dry sediment) (Fig. 6). The diatoms-to-stomatocysts ratio (D/C ratio) reaches maximum values (up to 122). The content of diatom inferred TP varies from 16 to 21 μg/l.

DZII (AD 1841-1970) is characterized by a greater number and diversity of benthic diatoms, while its D/C ratio and phosphorus content decrease. This zone is divided into two subzones (DZIIa and DZIIb).

DZIIa (AD 1841-1900) is distinguished by an increased concentration of diatom valves and chrysophyte cysts. D/C ratio decreases. The proportion of plankto-benthic species substantially increases due to *Pseudostaurosira brevistriata* and *Staurosira venter.* The number and percentage of benthic species increases: *Staurosirella lapponica, Amphora pediculus* (Kützing) Grunow in A.W.F.Schmidt 1875*, Halamphora thumensis, Cymbellafalsa diluviana, Matagloia lacustris,* and *Epithemia frickei.* The proportion of planktonic species is noticeable reduced due to *Aulacoseira ambigua.* On the contrary, *Stephanodiscus alpinus* and *Asterionella formosa var. formosa* Hassall 1850 become more abundant. *Stephanodiscus parvus* Stoermer & Håkansson 1984 appears. The number of planktonic, as well as plankto-benthic and benthic species increases. The Shannon diversity and evenness indices become higher, especially since AD 1868. The phosphorus content decreases to 15-16 μg/l, and it increases again to 16-19 μg/l since AD 1868.

DZIIb (AD 1900-1970). Planktonic diatoms become more abundant due to *Aulacoseira ambigua*. The proportion of plankto-benthic diatoms decreases due to *Pseudostaurosira brevistriata*, *Staurosira venter,* and *Staurosira construens.* Meanwhile, *Pantocsekiella ocellata* (Pantocsek) K.T.Kiss & E.Ács in Ács et al. 2016 and *Cyclotella krammeri* Håkansson 1990 are more widespread. The total number of benthic species remains the same, whereas the content of *Staurosirella lapponica* valves decreases, and that of *Karayevia clevei* increases. Diversity and evenness remain unchanged. Total phosphorus decreases from 18 to 16 μg/l in the period of AD 1944–1960. At the same time, the number of chrysophyte cysts increases.

DZIII (AD 1970-2021) is characterized by the higher content of planktonic diatoms due to *Pantocsekiella comensis, Stephanodiscus parvus, Asterionella formosa var. formosa,* and *Fragilaria crotonensis* Kitton 1869, to a lesser extent, *Stephanodiscus alpinus* and *Handmannia comta* species complex. Plankto-benthic and benthic diatoms are minor. The percentage of *Pseudostaurosira brevistriata*, *Staurosira venter*, and *S. construens* drops, whereas *Cyclotella krammeri* increases.

DZIIIa (AD 1970-1996) is characterized by acute fluctuations in *Aulacoseira ambigua* (with maxima at AD 1984-1996). The phosphorus increases reaching maximum values (19-21 μg/l) in 1978-1996. At the same time, the diversity and evenness indices decrease. The concentration of chrysophyte cysts decreases, and the diatoms-to-chrysophytes ratio increases.

DZIIIb (AD 1996-2021) is dominated by *Pantocsekiella comensis* with a drop in total phosphorus (up to 14 μg/l). In addition, *Aulacoseira ambigua* and *Stephanodiscus parvus* decrease. The evenness and diversity of diatoms increase slightly compared to the period from AD 1978 to AD 1996. The concentration of Chrysophyceae cysts increases.

3.6.3. Diatom record of BK1 lake sediments core (shallow-water part)

126 diatom algae species and varieties were identified by diatom analysis of the Lake Yaktykul sediment core. Of these, 94 species are benthic, 14 are planktonic, and 19 are plankto-benthic diatoms. The greatest abundance is characteristic for plankto-benthic species, and the greatest diversity is typical for benthic species. With respect to pH, most species are represented by alkaliphiles; in terms of saprobity, by oligosaprobes and β-mesosaprobes; in terms of trophic status, by meso-eutrophs and indifferents; and in terms of mineralization, by oligohalobes. The Shannon diversity index (H) varies from 2.0 to 2.8, and the evenness index varies from 0.5 to 0.7.

Three diatom zones were identified by stratigraphically constrained cluster analysis (Fig. 7).

DZI (AD 1794-1863) is dominated by *Pseudostaurosira brevistriata* and *Staurosira venter* . Subdominants include *Staurosira construens*, *Staurosira tabellaria*, *Staurosirella lapponica, S. pinnata*, *Amphora indistincta*, *A. pediculus*, and *Karayevia clevei*. *Halamphora thumensis, Cocconeis neothumensis*, *Staurosira binodis* (Ehrenberg) Lange-Bertalot in Hofmann, Werum &

Lange-Bertalot 2011, *Cymbellafalsa diluviana*, *Navicula cari* Ehrenberg 1836, and *Planothidium joursacense* (Héribaud-Joseph) Lange-Bertalot 1999 are constant in occurrence.

Planktonic species are dominated by *Aulacoseira ambigua*, while subdominants include *Pantocsekiella comensis*, *Stephanodiscus alpinus* and species referred to *Handmania comta* (according to (Kulikovskiy et al., 2016)). In addition, *Stephanodiscus neoastraea* Håkansson & Hickel 1986 is constant in occurrence. Few valves of *Asterionella formosa var. formosa*, *Fragilaria crotonensis*, as well as *Pantoksekiella ocellata* are noted. The Shannon diversity index is 2.1-2.5, and the evenness index is 0.6-0.7. Since 1841 AD, the number of benthic species rapidly increased, and the proportion of plankto-benthic species decreased. The number of Chrysophyceae stomatocysts varies greatly (from 1.7 to 0.7 mln per 1 g of dry sediment) (Fig. 8). The diatoms-to-stomatocysts ratio (D/C ratio) varies from 9 to 24. The content of diatom inferred TP varies from 14 to 19 µg L^{-1}.

DZII (AD 1863-1974) is distinguished by an increasing role of plankto-benthic diatoms and a decrease in *Staurosira venter*. This zone can be divided into three subzones: DZIIa, DZIIb, and DZIIc.

DZIIa (AD 1863-1900) is characterized by a steep increase in the concentration of diatom valves, largely due to *Pseudostaurosira brevistriata*. The proportion of *Staurosira venter*, *Cocconeis neothumensis*, *Gyrosigma attenuatum* (Kützing) Rabenhorst 1853, and *Staurosirella martyi* (Héribaud-Joseph) E.A.Morales & K.M.Manoylov 2006 falls. D/C ratio increases and varies between 23 and 52. Diversity and evenness are reduced (H=2.0-2.2, S=0.5-0.6). DI-TP varies from 13 to 18 µg L^{-1}.

DZIIb (AD 1900-1942). The concentration of diatoms, in particular, *Pseudostaurosira brevistriata* decreases, whereas *Staurosira venter* and *Staurosirella pinnata* become more abundant; *Staurosira aff. sviridae* Kulikovskiy, Genkal et Mikheeva 2011 appears (according to (Chudaev & Gololobova, 2016)). The content of benthic diatom valves increases. The role of *Cocconeis neothumensis*, *Gyrosigma attenuatum*, and *Staurosirella martyi* becomes more important. Diversity and evenness increase (H=2.2-2.4, S=0.6-0.7). D/C ratio decreases and varies between 6.5 and 14. DI-TP slightly decreases (no more than 18 µg L^{-1}).

DZIIc (AD 1942-1967) is characterized by an increasing role of planktonic diatoms due to *Aulacoseira ambigua*, *Pantoksekiella comensis*, and *Stephanodiscus alpinus.* The proportion of *Staurosira venter* and *Staurosira construens* is lower, whereas that of *Staurosirella lapponica* and *Cymbellafalsa diluviana* is higher. D/C ratio remains relatively low (7.7-14). DI-TP (14-20 µg L^{-1}) and diversity (H=2.2-2.8) are highly variable.

DZV (AD 1967-2021) is distinguished by a growing role of planktonic diatoms due to *Pantoksekiella comensis* and *Asterionella formosa var. formosa*. *Stephanodiscus parvus* appears since 1986 AD. *Staurosirella lapponica* decreases. The proportion of *Staurosira venter* and *S. construens* increases. The diatom concentration and D/C ratio (9-18) slightly increase. Diversity and evenness indices reach maximum values (H=2.6-2.8, S=0.7). DI-TP varies between 14 and 18 µg L^{-1}.

3.6.4. Determination of the influence of climatic parameters on diatom communities

Based on RDA of the BK3 reduced sequence (AD 1829–2021) with temperature climate parameters, mean annual air temperature (T annual), mean September air temperature (T September), mean August air temperature (T August), and mean April air temperature (T April) were significant environmental variables with λ_R/λ_P of 0.83, and variance explained of 30%. A unique significant variance ($p<0.05$) was observed for each of these variables (Supplementary Table S4). According to RDA of the Magnitogorsk climate data and diatom assemblages (AD 1936-2021), precipitation variables were not significant parameters.

According to the Pearson correlation analysis data, DI-TP had inverse correlation with T August (r=-0.4), especially since AD 1900 (r=-0.65). Chrysophyceae cysts negatively correlate (r=-52) with DI-TP and have no correlation with T August. D/C ratio also correlates with DI-TP (r=0.4). A direct correlation of planktonic (r=0.8) and an inverse correlation of benthic (r=-0.56) and plankto-benthic (r=-0.75) diatoms with T annual was revealed. The correlation is stronger, when *Aulacoseira ambigua* is removed from the analysis. DI-EC correlates with benthic diatoms, and Shannon diversity index correlates inversely with T September (r=0.6) and planktonic diatoms. Based on the Spearman Rank order correlation analysis between Magnitogorsk climate data and diatom analysis results, plankto-benthic diatoms directly and planktonic diatoms indirectly correlate with the precipitation in July (P July) (R=0.7 and -0.7).

RDA of the BK1 reduced sequence (AD 1828–2021) with temperature climate parameters demonstrated that T annual was the only significant environmental variable with the λ_R/λ_P of 0.6 and a variance explained of 7.7 %. Based on RDA of the BK1 reduced sequence (AD 1936–2021) with temperature and precipitation climate parameters, precipitations in May (P May) and March (P March) were significant variables. However, only P May (λ_R/λ_P of 0.83) was distinguished by a unique significant variance (16%, p=0.004).

Just like in BK3, we obtained a direct Pearson correlation of planktonic (r=0.7) and an inverse correlation of plankto-benthic (r=-0.6) diatoms with T annual. Benthic diatoms did not correlate with temperature parameters. Planktonic diatoms had a Spearman rank order correlation with P March (R=0.7). Diatom inferred total phosphorus had inverse Spearman correlation with precipitation in August (P August) (R=-0.56, $p<0.05$) and no correlations with other temperature and precipitation parameters estimated from the Orenburg (AD 1832-2021) or Magnitogorsk monitoring data (AD 1936-2021). In addition, DI-TP had inverse correlation with benthic diatoms, Shannon and evenness indices (r=-0.5), which correlated with P August (R=0.6-0.7) as well. In the contrast to deep-water part, Chrysophyceae cysts, diatom concentration, and D/C ratio did not associate with DI-TP. Chrysophyceae cysts correlated with mean March air temperature (T March) (r=0.5) and planktonic diatoms abundance (r=0.4).

4. Discussion

4.1. Assessment of the lake contamination in potential toxic elements and enrichment in PTEs over the past period of the lake history

According to the vertical profile distribution, Mo, V, Sr, Ba, and Cs accumulation in lake sediments in comparison with terrestrial substrates is explained by different natural factors. Sn, Sb, Bi, and W concentrations are partially related to the in-lake processes and to the industrial development. Until the beginning of the twentieth century, changes in the enrichment of Lake Yaktykul sediments in PTEs were probably explained by the natural factors. A rapid increase in microcharcoals in lake sediments in the first half of the twentieth century coincided with a greater enrichment of lake sediments in PTEs due to a growing anthropogenic activity in the region. Considerable enrichment of sediments in Zn, As, Sb, W, Bi, and Pb since the 1930-s coincided with the Magnitogorsk Iron and Steel Works foundation. At the same time, lake sediments became rapidly enriched in PTEs. The plant's production capacity and variety of products (iron ore, coke, cast iron, steel, and rolled products) continued to grow until the 1990s (Alekseev, 2001). A reduction in the Urals industry, in particular, in the operation of the Magnitogorsk Iron and Steel Works, related to the political upheavals, was observed in the 1990s. From about this time, the enrichment of lake sediments in above-mentioned elements decreased. The new industrial growth began only at the beginning of the twenty-first century. However, the production modernization made it possible to reduce hazardous emissions, and the sediment enrichment in PTEs did not increase. According to EIs values, enrichment of Lake Yaktykul in PTEs is lower than in the Southern and Middle Urals lakes of the forest zone (Maslennikova et al., 2023b). This fact and the permissible PTEs threshold values in the lake water make it possible to suppose a low PTEs contamination effect on the lake ecosystem changes.

4.2. Organic matter sources in Lake Yaktykul

Our research and literature data make it possible to determine an organic matter source in the Lake Yaktykul sediments, accumulated during various development periods of the lake. According to our data, terrestrial soils, rocks, and plants of the Lake Yaktykul catchment area are characterized by a light isotopic composition of organic carbon (-36...-25 ‰), while underwater aquatic plants have a heavier isotopic composition (-17...-8 ‰). This information is consistent with ((Boutton, 1991; Hoyer, Gu & Schelske, 1998). These study results are explained by the fact that terrestrial plants use atmospheric carbon dioxide for photosynthesis, and underwater aquatic vascular plants and algae use dissolved inorganic carbon with a heavier isotopic composition (Brenner et al., 1999). Based on the carbon isotopic composition, it is impossible to distinguish the organic matter sources such as underwater aquatic vascular plants and algae. The C/N ratio which is higher in aquatic vascular plants can be used for this purpose.

According to the previous studies, $\delta^{13}C$ of Lake Yaktykul sediments varied in the Holocene from -27.65 to -24.22 ‰ with C/N ~9 (Yusupova, Nourgalieva & Kuzina, 2022). Our research made it possible to obtain similar values: C/N = 8-12 and σC13 -24‰...-26‰. Relatively low contents of heavy carbon isotopes in organic matter of lake sediments we studied are indicative of predominant terrestrial C-3 plants as an organic matter source (Meyers & Benson, 1988). Meanwhile, C/N values (8-12) are indicative of the fact that the main organic matter source in Lake Yaktykul sediments was of autochthonous origin with a varying role of algae and vascular aquatic plants (Meyers, 1994). Such discrepancy can be related to the bacterial processes in lake sediments resulting in organic matter with a lighter composition of stable carbon isotopes (McKenzie, 1985; Krishnamurthy, Bhattacharya & Kusumgar, 1986; Strakhovenko et al., 2023). Lighter compositions of carbon isotopes against the background of low C/N could also be caused by erosion of the catchment area of the mountain-steppe lake whose soils and rocks, according to our data, were characterized by the lowest $\delta^{13}C$ values.

4.3. Major development stages of Lake Yaktykul over the past 300 years

Comparison of the comprehensive analysis results obtained for lake sediment cores made it possible to identify five lake development periods distinguished by considerable changes in the lake sediment record.

4.3.1. Oligo-mesotrophic or mesotrophic fresh lake with a depth of 20-25 m (AD 1718-1840)

The presence of oligotrophic and mesotrophic species of chironomids and diatoms and DI-TP variations point to the fact that the lake was mesotrophic or oligo-mesotrophic. *Aulacoseira ambigua* is predominant in the diatom community of the deep-water part of the lake likely due to a relatively long-term water mixing. According to GI-EC, the lake was freshwater with an electrical conductivity of no more than 223 µSm cm^{-1}. The period between AD 1718-1780 was characterized by lower EC, reduced contents of terrigenous drift elements, Sr and σC^{13}. An increase in Sr and σC^{13} since AD 1780 could be related to a greater role of aquatic vascular plants as an organic matter source.

4.3.2. An increase in the lake depth and a decrease in its trophic status against the background of a higher effective moisture and the climate cooling (AD 1840-1900)

According to the geochemical analysis data, this period is characterized by the lowest water electrical conductivity (no more than 210 µSm cm^{-1}). A decrease in the terrigenous component content can be explained by the catchment area afforestation recorded in the palynological diagram as an increase in the arboreal pollen. An increase in the organic nitrogen and carbon contents in the deep part of the lake can be explained by a decrease in terrigenous sediment mixing or a slight increase in lake productivity. An increased productivity in the deep-water part of the lake is not confirmed by the diatom and chironomid analysis data. For instance, DI-TP decreases in AD 1840-1860 and only then increases slightly. A major role of thecold stenothermic chironomid taxa and a minor role of *Tanytarsus pallidicornis*-type characteristic for a littoral of relatively productive lakes are indicative of the climate cooling and a lower lake productivity. According to the chironomid analysis data, the lake depth increases and reaches the maximum. An increase in HdV128 and open-water *Botryococcus* sp. can also be indicative of the lake deepening.

These changes can result from an increase in effective moisture of the study area due to a decrease in July temperature reconstructed by the chironomid analysis. A higher moisture content of the study area is confirmed by an increase in the *Pinus sylvestris* pollen and a decrease in the non-arboreal pollen (Maslennikova, 2020). Despite the fact that the lake deepening at this time is confirmed by various analyzes, the content of planktonic diatoms in the deep-water part decreases usually due to a decrease in depth. However, at that time, planktonic diatoms were dominated by the species *Aulacoseira ambigua* which prefers eutrophic and mesotrophic lakes and develops in the water mixing period. An increase in depth could lead to a more active stratification, a less active water mixing, and the limitation of biogenic elements to the lower part of the water column. These processes led to the reduction of *Aulacoseira ambigua* in the deep-water part of the lake. This conclusion also confirms a greater planktonic diatom diversity due to small cyclic and pennate species gained an advantage in the water stratification period (Rühland, Paterson & Smol, 2015). In the shallow part of the lake, *Aulacoseira ambigua* remained unchanged, whereas benthic diatoms rapidly decreased and planktonic-benthic diatoms increased. These data confirm the lake deepening in the period under consideration.

4.3.3. Lake depth decrease, carbonate accumulation, increasing role of aquatic vascular plants against the background of the climate warming and aggravated anthropogenic impact (AD 1900-1970)

Lake sediments accumulated in this period in the deep-water part of the lake are characterized by a decrease in total nitrogen and organic carbon likely due to a lower lake productivity or a sediment mixing with clastic material and authigenic carbonates. Based on the sediment core geochemistry, terrigenous drift chemical elements (Ti, Zr, REE, etc.) decreased, whereas Sr increased due to a sediment mixing with carbonate matter. A considerable increase in C/N (up to 12) is due to a greater role of aquatic vascular plants, as well as a possible increase in the allochthonous supply of organic matter. Meanwhile, the heavier carbon isotopic composition excludes the latter option. Higher σC^{13} can be explained by changes in the species composition of organic matter producers or an increase in the lake's trophic status. The lack of increase in DI-TP, total carbonб and nitrogen in sediments argues against an increase in the lake productivity. Based on these facts, we can conclude that this time was marked by a major role of aquatic vascular plants as a source of organic matter. In addition, the accumulation of calcite formed in an authigenically biochemogenic way as a result of photosynthesis became more active. This conclusion is confirmed by the chironomid analysis data on the deep-water part of the lake, which made it possible to reveal a substantial decrease in the lake depth. Planktonic diatoms become more abundant in the deep-water part due to *Aulacoseira ambigua* likely because of a more active water mixing as a result of a shallowing. In the shallow part of the lake, the content of benthic diatoms increases, whereas that of planktonic-benthic diatoms decreases. These data also confirm a lake shallowing.

The submerged and free-floating plant pollen appears in the sediment core of the shallow-water part of the lake. This fact, as well as a decrease in *Botryococcus* spp., and no more increase in HdV128 also confirm a fall in the lake level likely due to a reduced effective moisture of the study area. Alongside with that, the *Pinus sylvestris* pollen being a regional climate humidization indicator becomes more widespread (Maslennikova, 2020). The identified discrepancy is presumably indicative of the fact that not only climatic factors began to influence the lake level in the twentieth century. For instance, settlements were built on the lake shore in AD 1930, and water intake could affect the lake level.

4.3.4. An increase in depth, violent fluctuations in phosphorus in the deep and shallow parts of the lake against the background of the advancing climate warming and the limited lake flow (AD 1970-1996)

At that time, the lake was characterized by a decrease in water electrical conductivity, σC^{13}, C/N, and Sr (100-110 µg kg^{-1}) in lake sediments begun since the second half of the twentieth century. A gradual decrease in σC^{13} can be related to a lower abundance of aquatic vascular plants, as well as to a more active supply of isotopically lightened carbon of drainage waters (Rosenmeier et al., 2004; Choudhary, Routh & Chakrapani, 2009) or clastic material (Lozhkin et al., 2017). These data are confirmed by a sudden increase in terrigenous drift chemical elements. Changes in the lake sediment records are related to a gradual increase in the lake depth since the mid-twentieth century due to more abundant precipitations against the background of the slight climate cooling.

The chironomid analysis data record the lake deepening only since the 1980s. The last changes in the palynological record of the shallow part of the lake expressed as increase in Fungi, decrease in *Botryococcus* spp., and increase in Hdv128 were accompanied by an increase in planktonic diatoms. These changes occurred against the background of decreasing precipitation and increasing temperatures and could be related to a lake level rising and a coast erosion due to a flow regulation in AD 1980-2015.

4.3.5. Increased stratification against the background of the climate warming (AD 1995-2021)

The deep-water part of the lake is characterized by a decrease in DI-TP since AD 1995. Its shallow part is also characterized by a decrease in total phosphorus after a slight increase at the end of the twentieth century. The higher phosphorus content in 1995-2002 AD in the shallow part is likely related to lower precipitations led to a fall in the lake level, and therefore, a less active stratification. More abundant small cyclic diatoms, lower total phosphorus, and higher concentrations of cysts of Chrysophyceae in both deep and shallow parts of the lake are probably due to abnormally high temperatures during the growing season resulted in a more active water stratification. It should be noted that the higher stratification effect in the period under consideration was observed in both deep-water and relatively shallow parts of the lake. This process was due to the artificial regulation of the lake's flow enhanced the stratification effect caused by abnormally high temperatures due to the lake deepening and a decrease in its flow. Changes in the lake after the recovery of its flow in AD 2015 have not yet been recorded in the lake sediment record.

4.4. Drivers of the lake ecosystem shifts

4.4.1. Natural impact

Lake Yaktykul is characterized by a clear regularity previously noted for some lakes in the forest zone of the Southern Urals: just like lakes Turgoyak and Syrytkul, the content of small cyclic diatoms, as well as planktonic pennate diatoms, increases in the upper part of the cores, in both deep- and shallow-water parts (Maslennikova et al., 2023b). Such changes can be related to both the climate warming and the anthropogenic impact. An increase in *Asterionella formosa*, *Fragilaria crotonensis*, and especially *Stephanodiscus parvus* distinguished by a high TP-optimum can be related to the water reservoir eutrophication, as in lakes Turgoyak and Syrytkul. Meanwhile, *Pantocsekiella comensis* distinguished by a low TP optimum also increases. According to the RDA and correlation analysis data, diatom assemblages and water parameters of Lake Yaktykul are characterized by a close relationship to temperature and precipitation variations. In addition, a direct correlation of planktonic diatoms with the average annual temperature was found out for both deep- and shallow-water parts of the lake. In the deep-water part of the lake, the relationship between planktonic diatoms and average annual temperature increases with the removal of heavily silicified *Aulacoseira ambigua*. These data can be explained by the fact that small cyclic diatoms and planktonic pennate diatoms gain an advantage under the intensifying thermal stratification conditions caused by the climate change (Rühland, Paterson & Smol, 2015). Hence, an increase in planktonic diatoms in the Lake Yaktykul sediments, as well as in the Northern and Polar Urals lakes(Solovieva et al., 2005, 2008; Palagushkina, Nazarova & Frolova, 2020), is related primarily to the climate warming, rather than the anthropogenic impact, as in the forest lakes zones of the Southern Urals (Maslennikova et al., 2023b).

Lake Tavatui is located in the forest zone of the Middle Urals and characterized by a gradual increase in total phosphorus associated with increase in T annual and human impact since the beginning of the twentieth century (Maslennikova et al., 2023b). Moreover, Lake Tavatui is distinguished by higher phosphorus in the higher precipitation periods due to the supply of biogenic elements from the anthropogenically modified catchment (Maslennikova, 2022). This regularity was not noted for Lake Yaktykul. The phosphorus content varies in water, but does not tend to increase. The shallow part is characterized by an inverse, rather than direct, correlation between the phosphorus content and the amount of precipitation in August. A strong inverse correlation of phosphorus content with August temperature was determined for the deep-water part. A decrease in phosphorus content with increasing temperature is related to an increased stratification: nutrients released from the sediment are largely restricted to the hypolimnion, and phytoplankton production is supported mainly by the external load (Radbourne et al., 2019). Therefore, with the climate warming and increased stratification, the phosphorus content decreases in the epilimnion. In the shallow part of the lake, phosphorus content does not decrease with increasing August temperatures, but is inversely correlated with average August precipitation and benthic diatom content. The inverse correlation with benthic diatoms is explained by an increase in the number of planktonic-benthic species of diatoms and other algal species in the water column under the higher-phosphorus conditions. Accordingly, a transparency of the lake decreases, and this decrease affects the number of benthic species. Hence, an increase in the number of planktonic diatoms, the species composition of diatom assemblages, and total phosphorus variations in Lake Yaktykul are closely related to the climatic parameters.

4.4.2. Human impact

Changes in concentrations and enrichment in PTEs in the Lake Yaktykul core record only two events of metallurgical and mining history of the region: industrial growth in the Urals occurred following industrialization (1928–1941 AD) and a reduction in industry observed in the 1990s. The mining and metallurgy activity could lead to an increase in PTEs and a decrease in pH caused a reduction in productivity and plankton abundance and a decrease in the lake trophic status (Salonen, Tuovinen & Valpola, 2006; Tuovinen, Weckström & Salonen, 2012; Thienpont et al., 2016; Denisov et al., 2020). Changes in the lake ecosystem at this time are not evidently related to the mining and metallurgy activity possibly due to low enrichment of Lake Yaktykul in PTEs and permissible PTEs threshold values in the lake water.

Forest cutting in the 1920s, growth of population, and active construction of settlements on the lake shore in the 1930s could aggravate the catchment area erosion, increase the content of terrigenous components in lake sediments, and contribute to the lake eutrophication. On the contrary, this time is characterized by a decrease in terrigenous elements and productivity of the lake ecosystem due to the slight climate cooling. Alongside with that, a fall in the lake level since the beginning of the twentieth century can be explained by both a decrease in the effective moisture of the study area and an increase in water intake from the lake for economic needs and for the Kusimovsky Mine operation. The flow regulation, which had a very noticeable impact on the lakes of the forest zone in the Southern and Middle Urals and led to dramatic changes in the species composition of diatom assemblages and an increase in the trophic status (Maslennikova et al., 2023b), was recorded in the Lake Yaktykul chronicles only as a higher depth and a lower electrical conductivity. Variations in the total phosphorus content correspond to changes in the climatic parameters and have no evident relation to the anthropogenic impact. This fact can be explained by the difference in morphometric parameters and the level of anthropogenic impact on the compared lakes. Hence, the difference from lakes Tavatui and Syrytkul is mainly due to a significantly greater depth of Lake Yaktykul. Difference from Turgoyak having similar depth values and surface area/water volume ratio is related to a much more considerable anthropogenic impact on this lake.

Thus, the chronological boundaries of changes in the lake ecosystem, common for the deep and shallow parts of the lake, such as AD 1840 (1860), AD 1900 (1920), and AD 1970 were outlined by the multi-proxy analysis of Lake Yaktykul sediment cores. The lake ecosystem responds to the same factors in similar and different ways in different parts of the lake. This feature is due to a difference in lake depth, stratification, and its influence on the content of biogenic elements in the hypolimnion.

In contrast to the lakes located in the forest zone of the Southern Urals, Lake Yaktykul is characterized by a clear climate effect on the lake ecosystem development. Just like in the Northern and Polar Urals lakes, the number of planktonic diatoms increases correlating with an annual temperature in Lake Yaktykul, in both shallow and deep-water parts. Total phosphorus in the deep-water part of Lake Yaktykul is highly correlated with a temperature in August, and that in the shallow part is highly correlated with a precipitation amount in the same month.

The anthropogenic factors are almost inseparable from the climate effect. Lake Yaktykul is not characterized by an eutrophication trend related to an increase in anthropogenic impact in either shallow or deep-water parts. The mining and metallurgy effect is recorded only in the increasing enrichment of sediments in PTEs. A lower lake level in the first half of the twentieth century could be due to an increase in water intake for economic and industrial needs and also due to a decrease in the effective moisture of the area under consideration. Only an increase in the lake level since the 1980s can be explained mainly by the anthropogenic regulation of the lake's flow.

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Table 1. Location and morphometry of Lake Yaktykul

Parameter	**Value**
Cores BK1,2 latitude and longitude	53°59′30.00" N, 58°63′01.78″E
Cores BK 3,4 latitude and longitude	53°58′08.29″N, 58°63′10.54″E
Altitude, m a.s.l	438
Surface area, km^2	7.7
Shore length, km	11.2
Shore crook coefficient	1.14
Maximum water depth, m	28
Average water depth, m	10.6
Water volume, mln m^3	81.7
Openness coefficient	0.7
Water depth at BK1,2 cores site, m	14.5-14.9
Water depth at BK3,4 cores site, m	24.5-25.2
Catchment area, km^2	36.3
Catchment area/Lacustrine surface area	4.7
Lacustrine surface area/Water volume	0.09
Secchi disk depth at BK1,2 cores site, m	4-8.6
Secchi disk depth at BK3,4 cores site, m	5-9.9

Table 2. Hydrochemical parameters of Lake Yaktykul. Average values were calculated based on water samples collected in spring, summer, autumn of 2021, and August of 2022 and 2023. STDEV is a standard deviation, Mean - is average value. TN/TP - ratio of total nitrogen to total phosphorus. TSI - trophic state index. SD - Secchi disk depth.

Parameter	**Code**	**Unit**	**BK1**		**BK3**	
			Mean	STDEV	Mean	STDEV
Electrical conductivity	EC	µS cm^{-1}	181	18	182	19
Total water hardness	TWH	mmol L^{-1}	2.3	0.0	2.2	0.1
Alkalinity	Alk	mmol L^{-1}	2.2	0.0	2.2	0.0
Color of water	Color	Cr-Co scale	9.0	1.4	10	0.5
Permanganate value	PV	mgO L^{-1}	4.6	0.0	6.5	2.8
Salinity	Salinity	mg L^{-1}	205	2.8	203	5.1
Bicarbonate	HCO_3^-	µ eq L^{-1}	2179	42	2164	50
Chloride	Cl^-	µ eq L^{-1}	250	14	237	32
Sulphate	SO_4^{2-}	µ eq L^{-1}	289	29	317	52
Calcium	Ca^{2+}	µ eq L^{-1}	1248	102	1348	216
Magnesium	Mg^{2+}	µ eq L^{-1}	1033	102	812	276
Potassium	K^+	µ eq L^{-1}	61	34	47	14
Sodium	Na^+	µ eq L^{-1}	392	12	368	22
Phosphate phosphorus	PO_4-P	µg L^{-1}	2.4	3.2	1.3	0.3
Total phosphorus	TP	µg L^{-1}	9.8	2.5	8.6	2.1
Total nitrogen	TN	µg L^{-1}	364	142	338	158
TN/TP			32	9.4	37	15
TSI (SD)			37	5	34	4
TSI (TP)			37	4	35	4
TSI (TN)			39	6	36	11

Table 3. Parameters of surface and bottom water of Lake Yaktykul measured in August 2023.

Parameter	**Code**	**Unit**	BK1		BK3	
			surface	bottom	surface	bottom
Water depth	H	m	14.9		25.2	
Secchi disk	SD	m	8.6		9.9	
pH			8.8	7.8	8.9	8.8
Redox potential	Eh	mV	214	237	202	147
Electrical conductivity	EC	$\mu S\ cm^{-1}$	177	200	170	182
Chlorophill a	Chl a	$\mu g\ L^{-1}$	0.92	-	0.38	-
Temperature	t°	°C	22	12	22	7.1
Oxygen	O_2	%	98	37	110	5.7
		ppm	8.0	3.7	8.9	0.5
Phosphate phosphorus	PO_4-P	$\mu g\ L^{-1}$	1.3	4.6	1.3	4.6
Total phosphorus	TP	$\mu g\ L^{-1}$	7.5	19.2	5.2	10.8
Total nitrogen	TN	$\mu g\ L^{-1}$	170	120	70	90
TN/TP			23	6.3	13.5	8.3
TSI (SD)			29		27	
TSI (Chl a)			30	-	21	-
TSI (TP)			33	47	28	39
TSI (TN)			29	24	16	20

Figure legends

Fig. 1 Location of the study area in Russia (a), bathymetry and sampling site in the studied lake (b): yellow stars - the lake sediments cores (BK1-4) sampling sites; red circles with white numbers - places of water sampling and field measurements (depth, oxygen, electrical conductivity and pH); black numbers - water depth (color figure online).

Fig. 2 Geochemistry of Lake Yaktykul sediments cores (BK-3 and BK4, deep-water part). GI-EC – electric conductivity inferred with application of geochemical multiple regression model; Ter. comp. – terrigenous component calculated using Leonova and Bobrov (2012) approach; EI – enrichment index calculated according to Maslennikova et al., 2023a; $\delta^{13}C$ – stable carbon isotope ratio of sediments organic matter; C – content of carbon in sediments organic matter; N – content of nitrogen in sediments organic matter; C/N – ratio of elemental carbon to nitrogen in sediments organic matter. Error bars of terrigenous component and enrichment index are a standard deviation from values calculated with application of different trace elements (La, Zr, Hf, Nb, or Th) as a reference.

Fig. 3 Palynological record of the Lake Yaktykul sediments core (BK2, shallow-water part).

Fig. 4 Relative proportions of the most abundant chironomid taxa in the BK4 sediments core from the Lake Yaktykul deep-water part, Hill`s N2 diversity, PCA axes 1 scores for chironomid data; chironomid-inferred mean July air temperature (T July, °C) and water depth (WD, m), and results of Modern Analogue (MAT) tests for reconstructed T July and WD with reference line at the 5th percentile of all squared chord distances of the modern data (no good analogues). Reference lines for the reconstructed parameters show modern values for T July (17.3 °C) and WD (24 m). Chironomid taxa are sorted by weighted average.

Fig. 5 Diatom stratigraphy of the Lake Yaktykul sediment core (BK3 sediments core, deep-water part) (color figure online).

Fig. 6 Climate parameters variations and changes of indices of diversity and evenness, ecological groups of diatoms, ratio of diatoms to Chrysophyceae stomatocysts ratio, concentration of Chrysophyceae stomatocysts and diatoms, diatom-inferred parameters (TP - total phosphorus, EC - electrical conductivity) for BK3 sediments core (deep-water part). Climate parameters: temperatures from Orenburg meteodata (http://www.pogodaiklimat.ru/history/35023.htm) in orange color; temperature from Magnitogorsk data (http://www.pogodaiklimat.ru/history/28838_2.htm) in red color and precipitation in blue color (color figure online).

Fig. 7 Diatom stratigraphy of the Lake Yaktykul sediment core (BK1, shallow-water part) (color figure online).

Fig. 8 Climate parameters variations and changes of indices of diversity and evenness, ecological groups of diatoms, ratio of diatoms to Chrysophyceae stomatocysts ratio, concentration of Chrysophyceae stomatocysts and diatoms, diatom-inferred parameters (TP - total phosphorus, EC - electrical conductivity) for BK1 sediments core (shallow-water part). Climate parameters: temperatures from Orenburg meteodata (http://www.pogodaiklimat.ru/history/35023.htm) in orange color; temperature from Magnitogorsk data (http://www.pogodaiklimat.ru/history/28838_2.htm) in red color and precipitation in blue color (color figure online).

Fig. 1

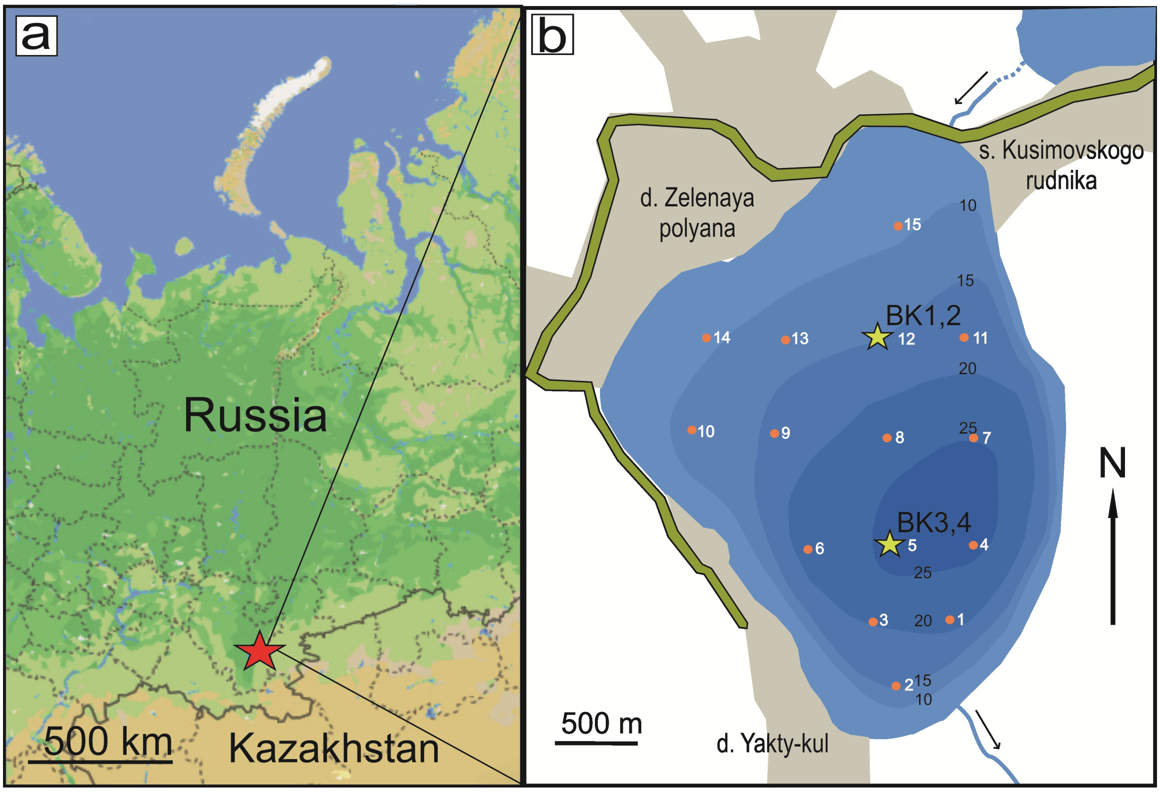

a
Russia
500 km
Kazakhstan
b
d. Zelenaya
polyana
s. Kusimovskogo
rudnika
d. Yakty-kul
BK1,2
BK3,4
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
10
15
20
25
25
20
15
10
500 m
N

Fig. 2

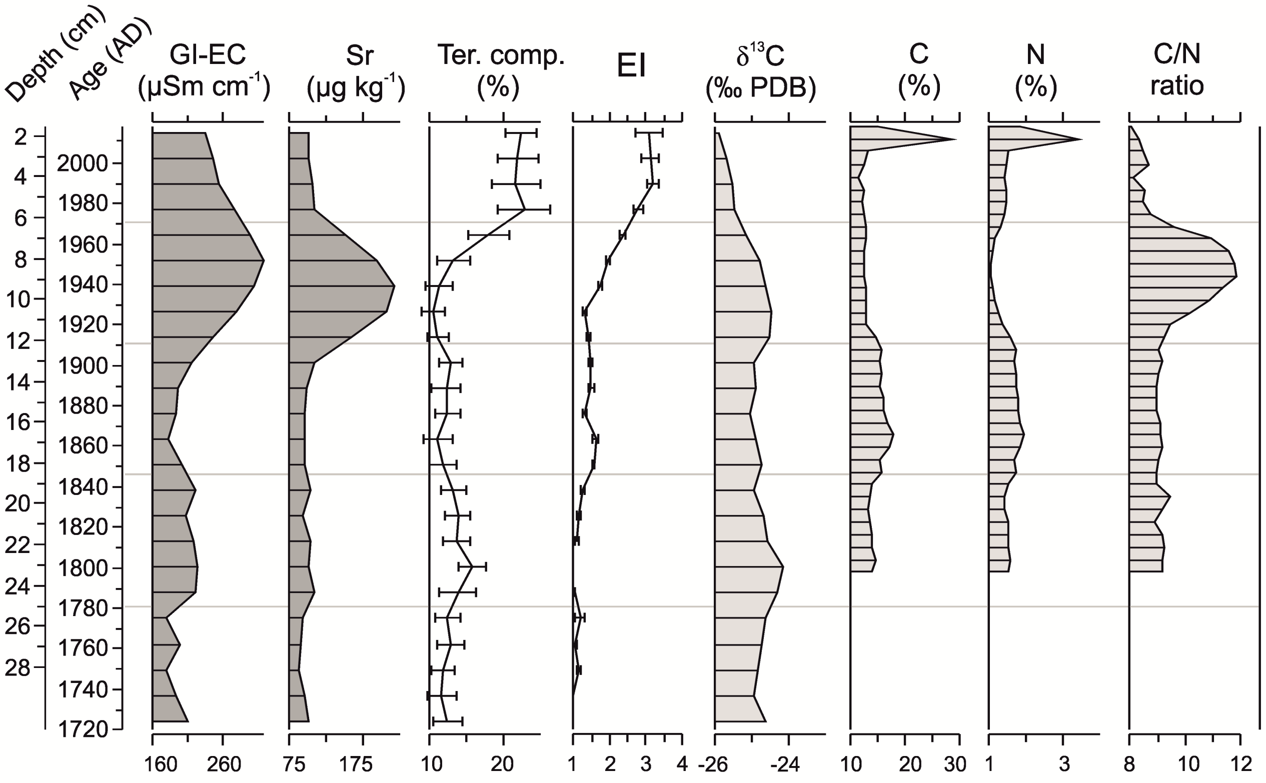

Depth (cm)
Age (AD)
GI-EC (μSm cm-1)
Sr (μg kg-1)
Ter. comp. (%)
EI
δ13C (‰ PDB)
C (%)
N (%)
C/N ratio
2
4
6
8
10
12
14
16
18
20
22
24
26
28
2000
1980
1960
1940
1920
1900
1880
1860
1840
1820
1800
1780
1760
1740
1720
160
260
75
175
10
20
1
2
3
4
-26
-24
10
20
30
1
3
8
10
12

Fig. 3

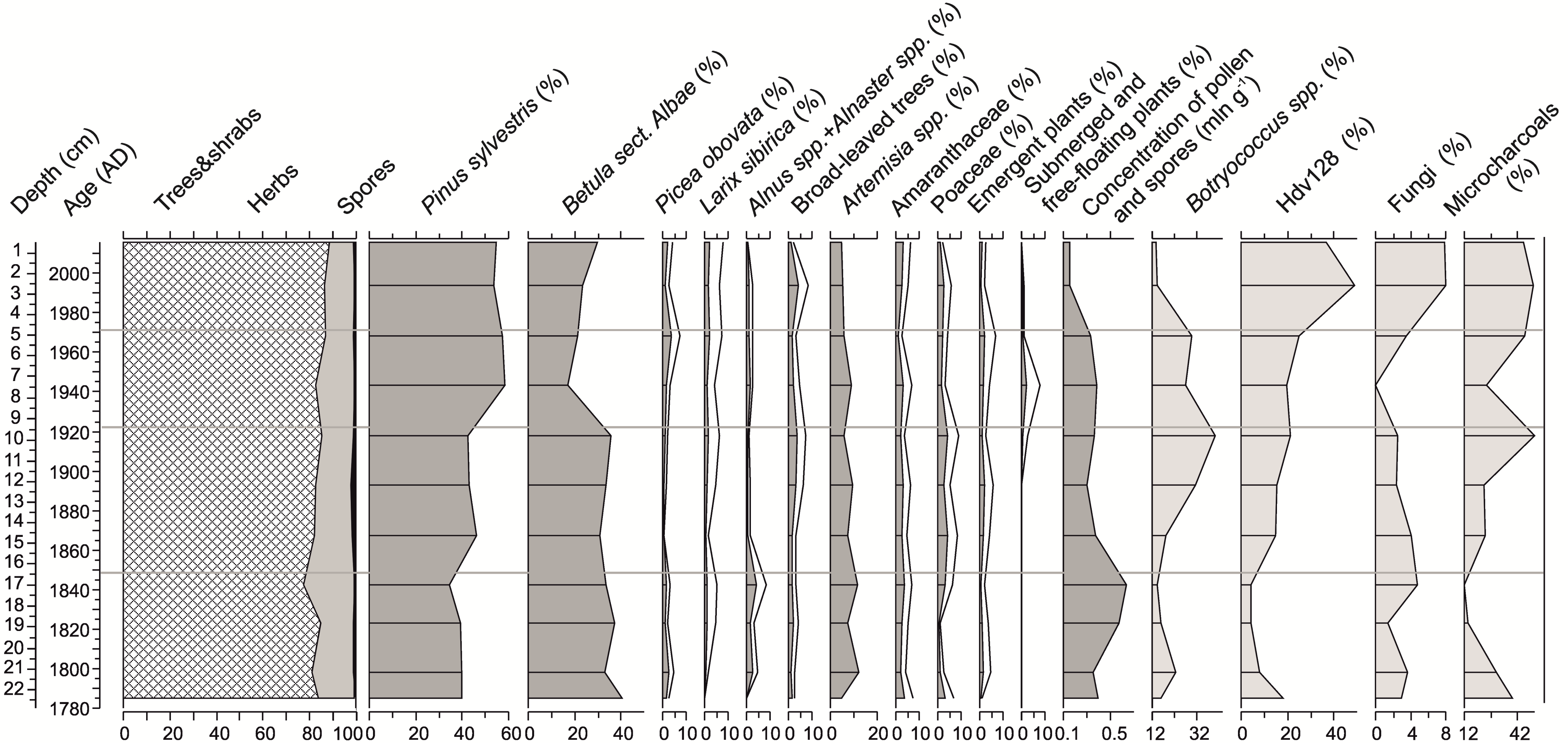

Depth (cm)
Age (AD)
Trees&shrabs
Herbs
Spores
Pinus sylvestris (%)
Betula sect. Albae (%)
Picea obovata (%)
Larix sibirica (%)
Alnus spp.+Alnaster spp. (%)
Broad-leaved trees (%)
Artemisia spp. (%)
Amaranthaceae (%)
Poaceae (%)
Emergent plants (%)
Submerged and free-floating plants (%)
Concentration of pollen and spores (mln g-1)
Botryococcus spp. (%)
Hdv128 (%)
Fungi (%)
Microcharcoals (%)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
2000
1980
1960
1940
1920
1900
1880
1860
1840
1820
1800
1780
0 20 40 60 80 100
0 20 40 60
0 20 40
0 10
0 10
0 10
0 10
0 20
0 10
0 10
0 10
0 10
0.1 0.5
12 32
0 20 40
0 4 8
12 42

Fig. 4

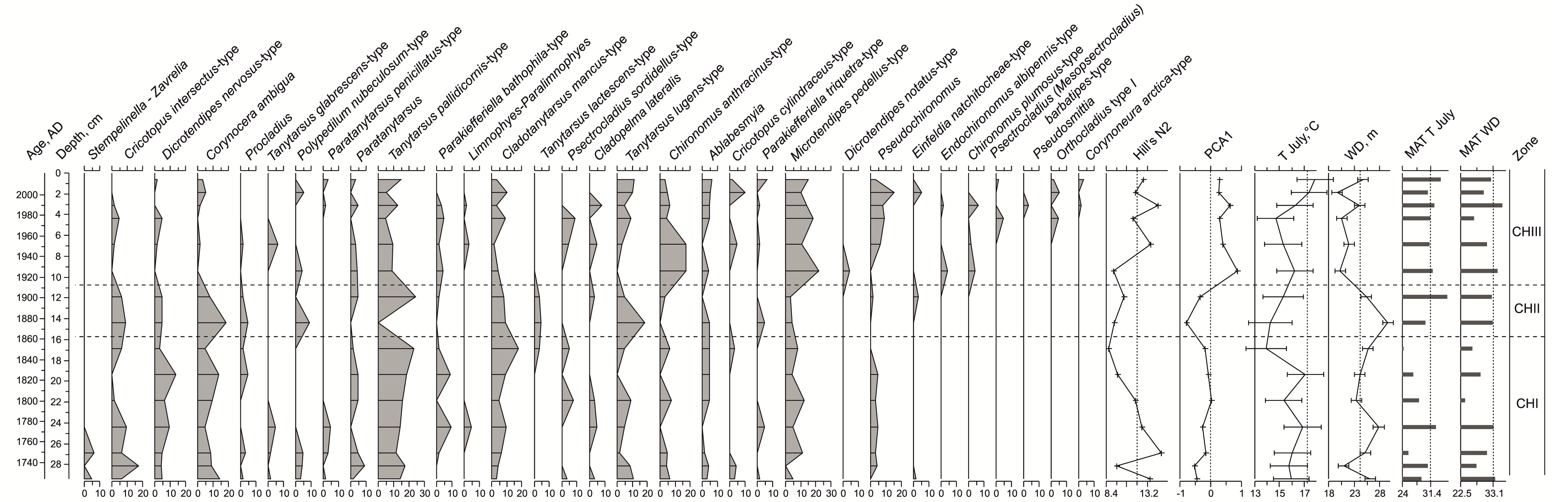

Age, AD
Depth, cm
Stempelinella - Zavrelia
Cricotopus intersectus-type
Dicrotendipes nervosus-type
Corynocera ambigua
Procladius
Tanytarsus glabrescens-type
Polypedilum nubeculosum-type
Paratanytarsus penicillatus-type
Paratanytarsus
Tanytarsus pallidicornis-type
Parakiefferiella bathophila-type
Limnophyes-Paralimnophyes
Cladotanytarsus mancus-type
Tanytarsus lactescens-type
Psectrocladius sordidellus-type
Cladopelma lateralis
Tanytarsus lugens-type
Chironomus anthracinus-type
Ablabesmyia
Cricotopus cylindraceus-type
Parakiefferiella triquetra-type
Microtendipes pedellus-type
Dicrotendipes notatus-type
Pseudochironomus
Einfeldia natchitocheae-type
Endochironomus albipennis-type
Chironomus plumosus-type
Psectrocladius (Mesopsectrocladius) barbatipes-type
Pseudosmittia
Orthocladius type I
Corynoneura arctica-type
Hill's N2
PCA1
T July,°C
WD, m
MAT T July
MAT WD
Zone
2000
1980
1960
1940
1920
1900
1880
1860
1840
1820
1800
1780
1760
1740
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
CHIII
CHII
CHI
0 10 0 10 20 0 10 20 0 10 20 0 10 0 10 0 10 0 10 0 10 0 10 20 30 0 10 0 10 0 10 20 0 10 0 10 0 10 0 10 20 0 10 20 0 10 0 10 0 10 0 10 20 30 0 10 0 10 20 0 10 0 10 0 10 0 10 0 10 0 10 0 10
8.4
13.2
-1
0
1
13
15
17
18
23
28
24
31.4
22.5
33.1

Fig. 5

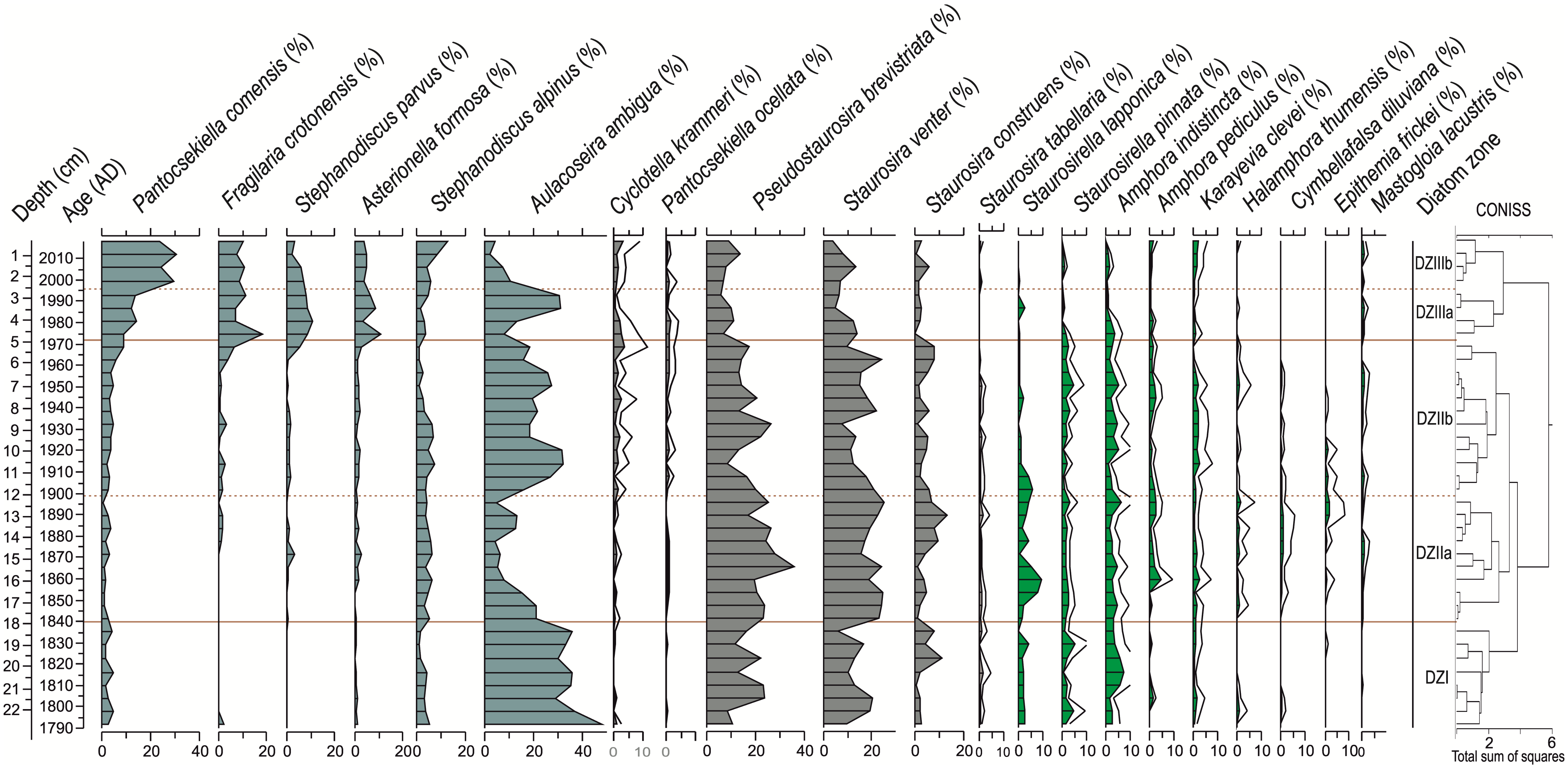

Depth (cm)
Age (AD)
Pantocsekiella comensis (%)
Fragilaria crotonensis (%)
Stephanodiscus parvus (%)
Asterionella formosa (%)
Stephanodiscus alpinus (%)
Aulacoseira ambigua (%)
Cyclotella krammeri (%)
Pantocsekiella ocellata (%)
Pseudostaurosira brevistriata (%)
Staurosira venter (%)
Staurosira construens (%)
Staurosira tabellaria (%)
Staurosirella lapponica (%)
Staurosirella pinnata (%)
Amphora indistincta (%)
Amphora pediculus (%)
Karayevia clevei (%)
Halamphora thumensis (%)
Cymbellafalsa diluviana (%)
Epithemia frickei (%)
Mastogloia lacustris (%)
Diatom zone
CONISS
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
2010
2000
1990
1980
1970
1960
1950
1940
1930
1920
1910
1900
1890
1880
1870
1860
1850
1840
1830
1820
1810
1800
1790
DZIIIb
DZIIIa
DZIIb
DZIIa
DZI
0 20 40
0 20
0 20
0 20
0 20
0 20 40
0 10
0
0 20 40
0 20
0 20
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0
2 6
Total sum of squares

Fig. 6

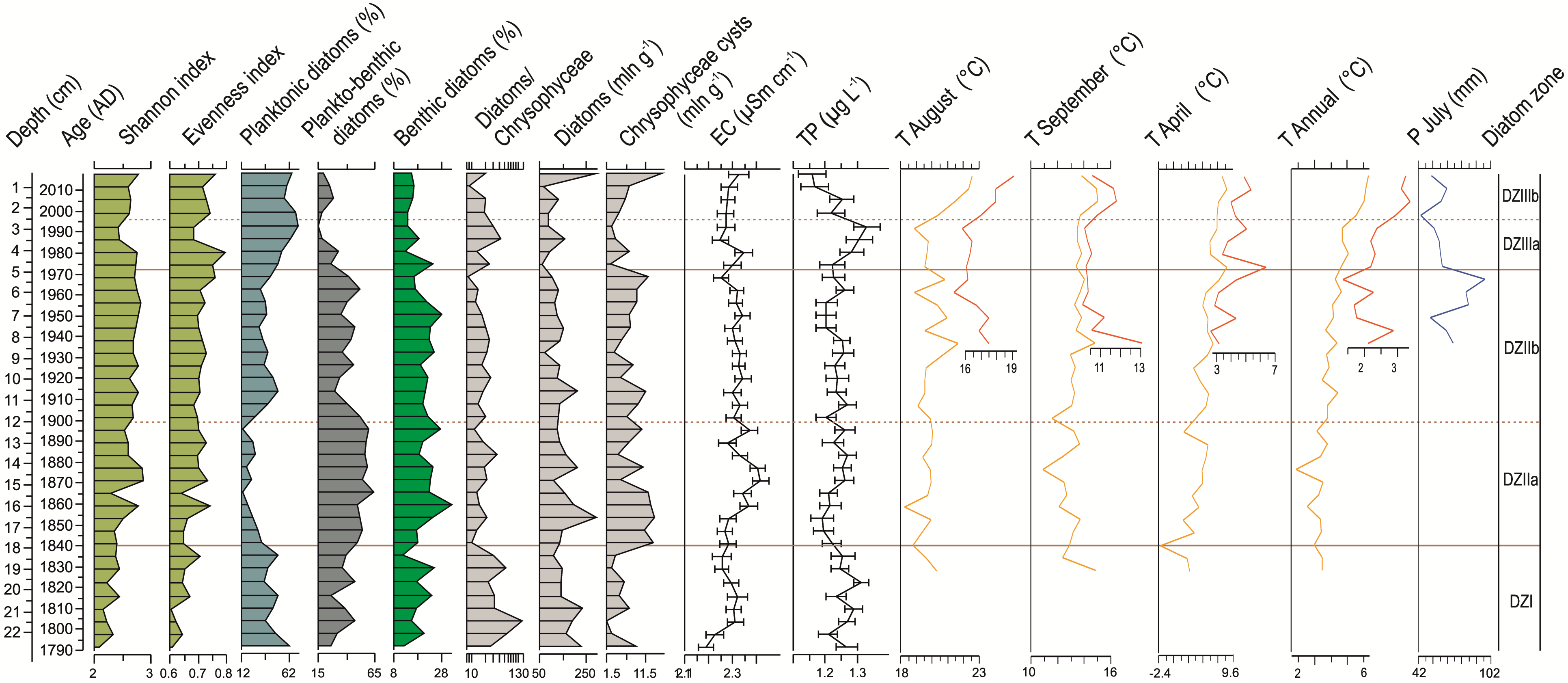
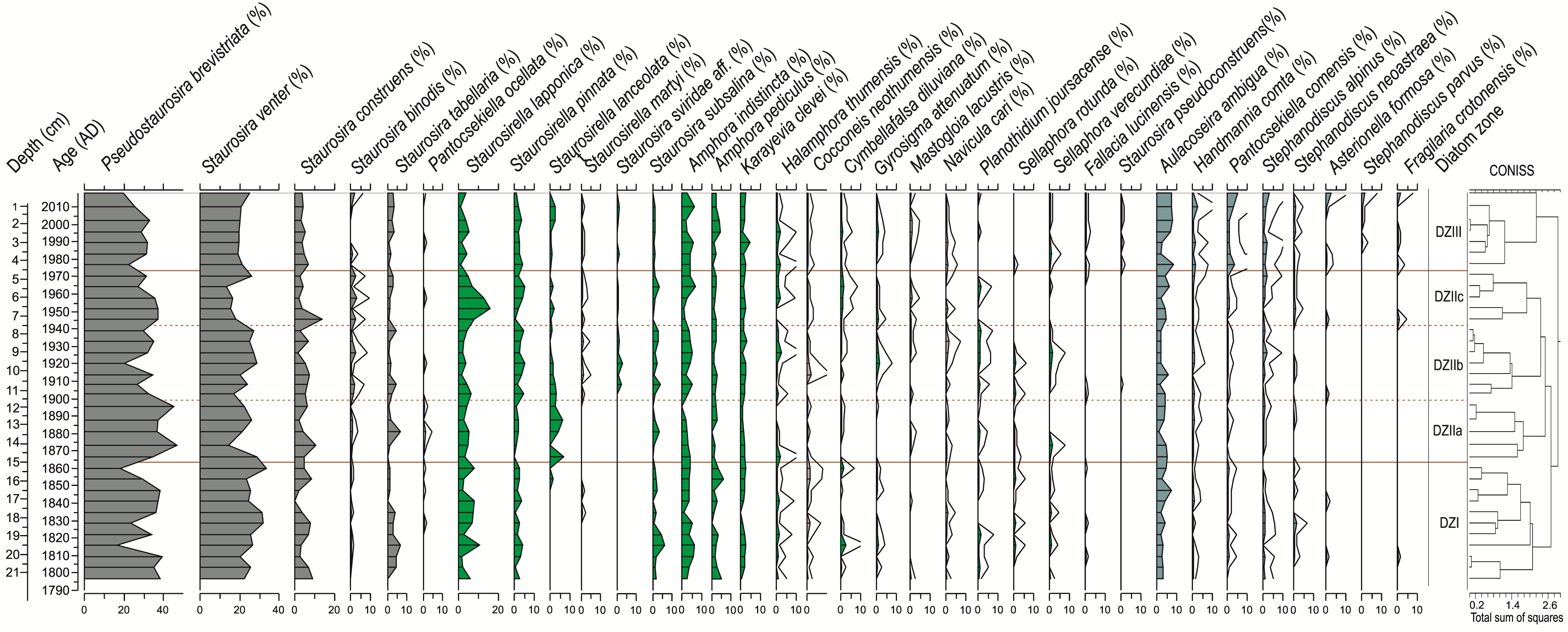
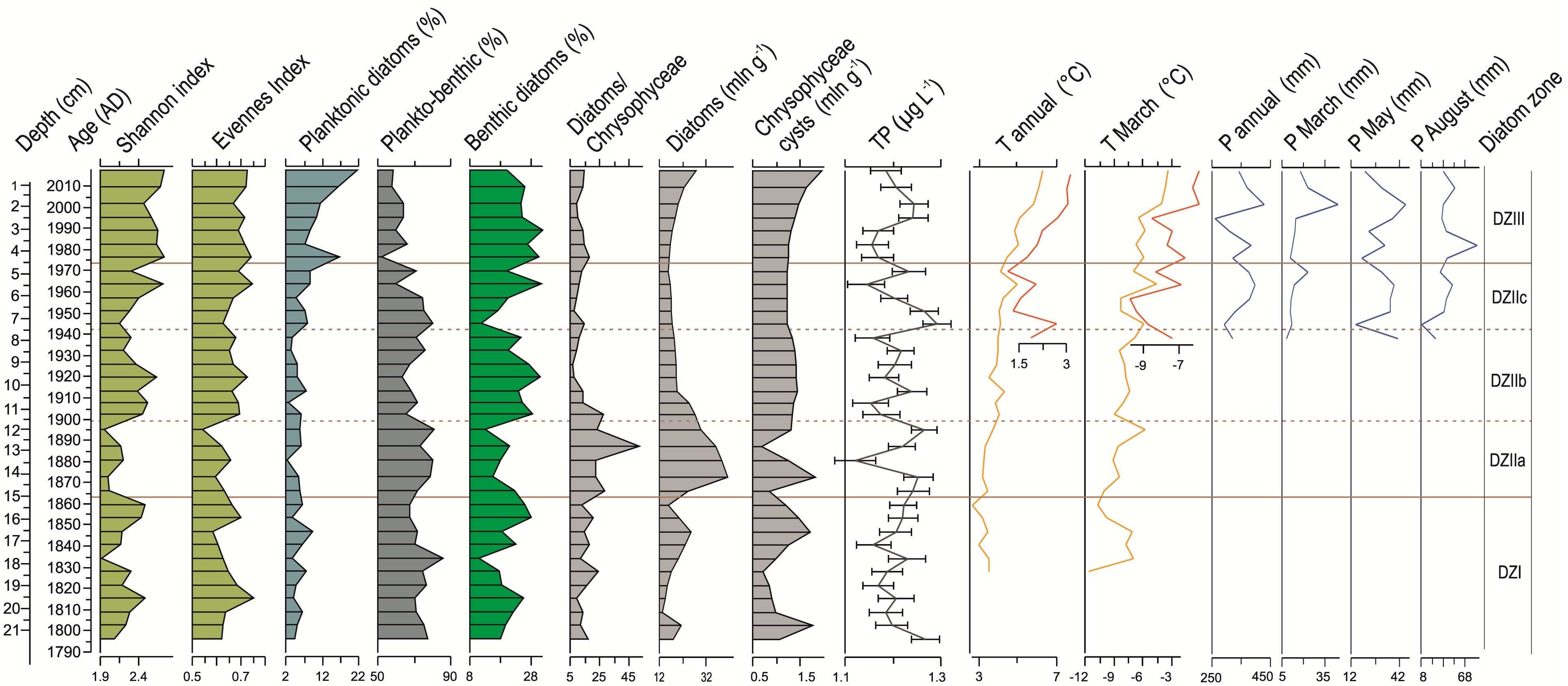

Depth (cm)
Age (AD)
Shannon index
Evenness index
Planktonic diatoms (%)
Plankto-benthic diatoms (%)
Benthic diatoms (%)
Diatoms/ Chrysophyceae
Diatoms (mln g^{-1})
Chrysophyceae cysts (mln g^{-1})
EC (µSm cm^{-1})
TP (µg L^{-1})
T August (°C)
T September (°C)
T April (°C)
T Annual (°C)
P July (mm)
Diatom zone
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
2010 2000 1990 1980 1970 1960 1950 1940 1930 1920 1910 1900 1890 1880 1870 1860 1850 1840 1830 1820 1810 1800 1790
2 3
0.6 0.7 0.8
12 62
15 65
8 28
10 130
50 250
1.5 11.5
2.1 2.3
1.2 1.3
18 23
16 19
10 16
11 13
-2.4 9.6
3 7
2 6
2 3
42 102
DZIIIb
DZIIIa
DZIIb
DZIIa
DZI

Fig. 7



Depth (cm)
Age (AD)
Pseudostaurosira brevistriata (%)
Staurosira venter (%)
Staurosira construens (%)
Staurosira binodis (%)
Staurosira tabellaria (%)
Pantocsekiella ocellata (%)
Staurosirella lapponica (%)
Staurosirella pinnata (%)
Staurosirella lanceolata (%)
Staurosirella martyi (%)
Staurosira sviridae aff. (%)
Staurosira subsalina (%)
Amphora indistincta (%)
Amphora pediculus (%)
Karayevia clevei (%)
Halamphora thumensis (%)
Cocconeis neothumensis (%)
Cymbellafalsa diluviana (%)
Gyrosigma attenuatum (%)
Mastogloia lacustris (%)
Navicula cari (%)
Planothidium joursacense (%)
Sellaphora rotunda (%)
Sellaphora verecundiae (%)
Fallacia lucinensis (%)
Staurosira pseudoconstruens(%)
Aulacoseira ambigua (%)
Handmannia comta (%)
Pantocsekiella comensis (%)
Stephanodiscus alpinus (%)
Stephanodiscus neoastraea (%)
Asterionella formosa (%)
Stephanodiscus parvus (%)
Fragilaria crotonensis (%)
Diatom zone
CONISS
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
2010
2000
1990
1980
1970
1960
1950
1940
1930
1920
1910
1900
1890
1880
1870
1860
1850
1840
1830
1820
1810
1800
1790
DZIII
DZIIc
DZIIb
DZIIa
DZI
0 20 40
0 20 40
0 20
0 10
0 10
0 10
0 20
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0 10
0.2 1.4 2.6
Total sum of squares

Fig. 8


Depth (cm)
Age (AD)
Shannon index
Evennes Index
Planktonic diatoms (%)
Plankto-benthic (%)
Benthic diatoms (%)
Diatoms/ Chrysophyceae
Diatoms (mln g-1)
Chrysophyceae cysts (mln g-1)
TP (µg L-1)
T annual (°C)
T March (°C)
P annual (mm)
P March (mm)
P May (mm)
P August (mm)
Diatom zone
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
2010 2000 1990 1980 1970 1960 1950 1940 1930 1920 1910 1900 1890 1880 1870 1860 1850 1840 1830 1820 1810 1800 1790
1.9 2.4
0.5 0.7
2 12 22
50 90
8 28
5 25 45
12 32
0.5 1.5
1.1 1.3
3 7
1.5 3
-12 -9 -6 -3
-9 -7
250 450
5 35
12 42
8 68
DZIII
DZIIc
DZIIb
DZIIa
DZI