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Holocene environments in the Middle Urals: Palaeolimnological proxies from the Lake Tavatui (Russia)

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ABSTRACT

New palaeolimnological proxies from the Lake Tavatui sediments core contributed to the reconstruction of the Middle Urals environments from over 11.9 cal ka BP and estimation of the main drivers of the lake ecosystem changes.

The comparison of diatom and pollen records enables a more robust and detailed reconstruction of the Holocene Middle Urals environments than the ones previously available. In most cases, the Lake Tavatui pollen and diatom data were in a good agreement and complemented each other. The diatom and pollen records reflect cold and rather dry conditions at 11.9–11.65 cal ka BP, climate warming and slight increase in effective moisture between 11.65 and 10.35 cal ka BP. The climate got colder at 10.35–7.9 cal ka BP. The warming with a great increase in effective moisture at 7.9–6.5 cal ka BP was followed by cooling at 6.5–4.6 cal ka BP. The period from 4.6 to 3.0 cal ka BP was marked by slight warming and unstable conditions. The subsequent cooling continued from 3.0 to 1.3 cal ka BP. The pollen and diatom data reconstructions for the period between 1.3 cal ka BP and 2009 AD are controversial possibly due to human impact on the lake and catchment.

The analysis of the diatom assemblages as well as diatom inferred total phosphorus (DI–TP) and electrical conductivity (DI–EC) made it possible to determine five main development stages of the Lake Tavatui. According to the quantitative reconstruction, Lake Tavatui remained in the freshwater range with DI–EC variation from 75 to 290 μS cm^{-1} throughout the lake development. The trophic status changed many times and varied between oligo-mesotrophic and eutrophic. The highest DI–TP values were observed for the period between 7.9 and 6.5 cal ka BP and since the 1990s. Until 1932-1943 AD, shifts in the lake ecosystem can be explained by direct and catchment-mediated natural climate change. From the mid-nineteenth century, the lake water phosphorus content changed in accordance with the main trend of increasing annual temperature. From 1932–1943 AD the main driver of DI–TP variations was the delivery of catchment-derived nutrients into the lake, which increased in periods with high precipitation. This change in the lake ecosystem response to climatic parameters could be associated with human impact which contributed to nutrients content in the catchment.

1. Introduction

The Middle Urals palaeoenvironmental reconstructions provide the link between palaeorecords of Europe and Asia. Previously, the Holocene in the Middle Urals was studied mainly by the spore–pollen analysis of peat cores. These investigations allowed to establish climate changes and major vegetation stages in the Urals (Khotinsky, 1977). These data were updated by the palynological analysis and AMS ^{14}C dating of the Middle Urals peat cores (Zaretskaya et al., 2014; Panova and Antipina, 2016; Lapteva et al., 2020) and Lake Tavatui sediment core (Maslennikova et al., 2016b). However, non-climatic factors could have a strong impact on the vegetation. This is especially true for the forest zone, where the change from one species to another can be determined by the natural vegetation succession. In addition, vegetation could be influenced to some extent by humans (Jacques et al., 2015). Therefore, other proxies are needed for a clear understanding of the Middle Urals environmental changes. Diatoms are commonly used to reconstruct past environments due to their sensitivity to a range of environmental variables. Analysis of a 72-lake regional diatom dataset indicated that electrical conductivity (EC) was the most important environmental variable explaining diatom assemblage variance. Ionic composition and nutrients were the next significant independent variables

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(Maslennikova, 2020). Lake water salinity and electrical conductivity are climate-dependent limnological variables associated with effective moisture and increase towards the east and south in the Urals (Andreeva, 1973). Diatom-inferred electrical conductivity can be used to reconstruct effective moisture from Uralian lacustrine sediments. Climate warming usually leads to a higher lake productivity due to increase in water temperature, longer growing season, and greater nutrients input from the catchment under intensification of microbiological processes. Cooling often leads to the opposite result (Pienitz et al., 1999; Jones et al., 2011; Schleusner et al., 2014). In this study, the changes in lake productivity and water EC in Lake Tavatui are estimated based on quantitative total phosphorus (TP), EC reconstructions, and the shifts in diatom taxa with known ecological preferences. Thus, the first aim of this study is to compare the quantitative and qualitative diatom analysis data with palynological proxies to refine the Middle Urals palaeoenvironmental reconstructions over the past 11.9 cal ka BP.

Palaeolimnological proxies provide information not only about changes in the palaeoclimate, but also about the response of the lake ecosystem to natural and human-induced impact. The hydrochemical parameters of lakes depend on a large number of natural factors, including both direct climate impact and its indirect effects related to catchment changes, vegetation and soil development (Fritz and Anderson, 2013). In addition, drastic environmental changes and lake ecosystem shifts could be caused by human impact (Maslennikova et al. al., 2016a; Wengrat et al., 2018; Alenius et al., 2020; Denisov et al., 2020; Zawiska et al., 2020). Study of the lake ecosystem response to environmental changes is necessary to understand the causes of rapid and adverse shifts in lakes of different climatic zones over the past 100–150 years. Thus, the second aim is to determine the main natural and human drivers on the Lake Tavatui ecosystem development during the Holocene.

2. Regional settings

2.1. Physical and geological characteristics of the area

Lake Tavatui (57°08′01.97″N, 60°10′57.43″E, 259 m a.s.l.) is located 35 km south of Nevyansk, on the Eastern Slope of the Middle Urals, the region of the Urals with the lowest elevation (Fig. 1). The present-day climate of the studied region is continental, with an annual precipitation of 578 mm yr^{-1}, an average July air temperature of +17.6 °C and an average January air temperature of −14.4 °C (based on 2001–2020 data from Nevyansk meteorological station).

The western air mass transport is predominant. Atlantic cyclones bring warm and wet air masses to the Urals. Arrival of Atlantic air is accompanied by cooler temperature and higher precipitation in summer and by warming in winter (Orlenok et al., 1998). The second component of the air mass circulation in the region is meridional transport associated with the flow of Arctic air from the north and tropical air from Central Asia. Arctic air arrival causes cooling, and tropical air brings hot weather in spring and summer. The meridional circulation facilitated by the low altitude of the Middle Urals mountains leads to weather instability, especially in autumn and summer. In winter months, the Middle Urals is also influenced by the Siberian High which causes extremely frosty weather with the lowest air temperatures of the year.

Modern boreal forest in the area is composed of pine (*Pinus sylvestris* Linnaeus, 1753) mixed with spruce (*Picea obovata* Ledebour, 1833) and fir (*Abies sibirica* Ledebour, 1833). Birch (*Betula pendula* Roth) is widespread in the human-modified area.

Lake Tavatui lies in the Western Verkhisetsky geological complex. The bedrock is composed of Carboniferous quartz diorites, tonalites, and plagiogranites. Tonalites are broken by granodiorites to the south of Lake Tavatui and by Verkhisetsky granites to the west of it. The bedrocks are overlain by Neo-Pleistocene deposits as clays and loams with crushed underlying rocks, Holocene peat sediments to the south and lake sediments to the north (Kalugina et al., 2017).

Lake Tavatui is one of the largest lakes in the Middle Urals (Table 1).

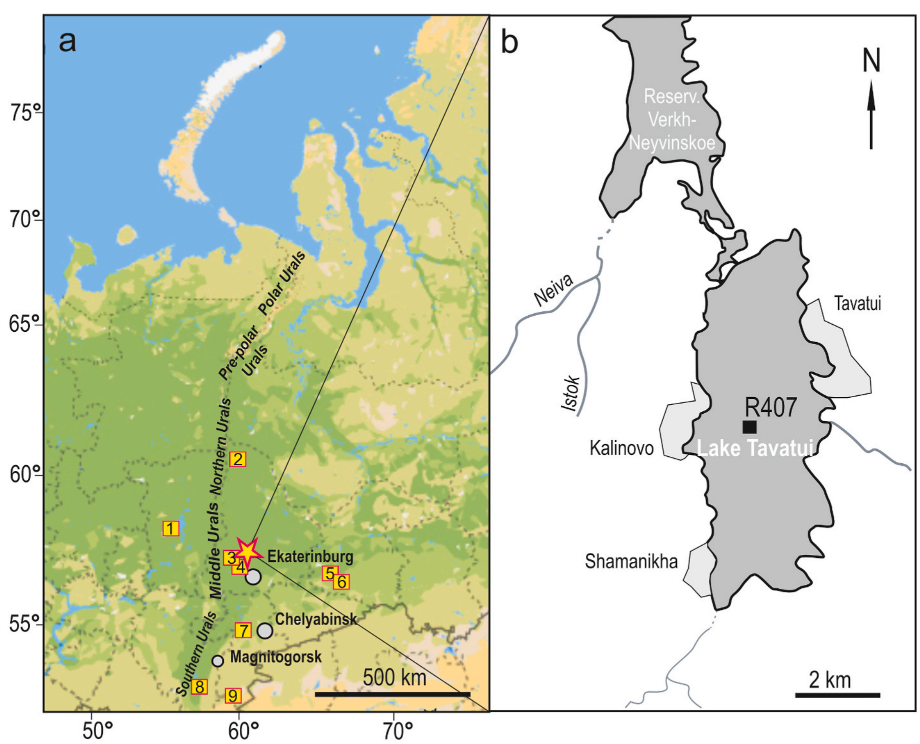

Fig. 1. (a) Location of Lake Tavatui (star) and sediment cores (quadrangles) discussed in the text: 1 – Shumilovskikh et al., 2020; 2 – Antipina et al., 2014; 3 and 4 – Zaretskaya et al., 2014; Panova and Antipina (2016); 5 – Ryabogina et al., 2019; 6 – Nasonova et al., 2019; 7 – Maslennikova et al., 2016; Maslennikova (2020); 8 – Maslennikova (2020); 9 – Stobbe et al., 2016; (b) location of the core (R407) and the map of the Lake Tavatui region (b).

Table 1
Lake Tavatui parameters. Water samples were collected on June 10, 2014. Water samples for total phosphorus analysis were collected on June and August 2014, 2019 and 2021.

Lake parameters	Surface water	Bottom water
Surface area (ha)	2100	
Maximum water depth (m)	9	
Average water depth (m)	6	
Catchment area square (ha)	10400	
Water volume (mln m^3)	124	
Coring depth (m)	7.5	
Salinity (mg L^{-1})	108	109
Electrical conductivity (μS cm^{-1})	120	122
Total water hardness (mmol L^{-1})	1.21	1.15
Alkalinity (μeq L^{-1})	0.84	0.8
pH	7.46	7.62
Permanganate value (mgO L^{-1})	4.74	4.74
HCO_3^- (mg L^{-1})	51.24	48.6
Cl^- (mg L^{-1})	7.09	7.09
SO_4^{2-} (mg L^{-1})	22.08	22.34
NO_2^- (mg L^{-1})	0.005	0.008
NO_3^- (mg L^{-1})	0.1	0.3
NH_4^+ (mg L^{-1})	0.11	0.11
PO_4^{3-} (mg L^{-1})	<0.01	<0.01
Total phosphorus (μg L^{-1})	26–36	18
Ca^{2+} (mg L^{-1})	14.83	14.88
Mg^{2+} (mg L^{-1})	5.71	4.98
K^+ (mg L^{-1})	2.32	2.19
Na^+ (mg L^{-1})	5.3	5.4

Lake Tavatui is freshwater, calcium bicarbonate-dominated with sulfate as the sub-dominant anion and magnesium as the sub-dominant cation. According to the relationship of lake productivity to average concentrations of epilimnetic total phosphorus (Wetzel, 2001), Lake Tavatui varied between meso-eutrophic and eutrophic level. Until the eighteenth century, the lake was much smaller. The Lake Tavatui level rose by 2–3 m with an increase in surface area after the plant foundation by Prokofiy Demidov in 1762, following the construction of a dam on the Neiva River. Then in 1914–1915, after the construction of the Kalinovskiy plant, an artificial passage was made to the east of the old channel connecting the Lake Tavatui with the Verkh-Neyvinsky pond (Lozhkin, 1971).

2.2. Humans in the Middle Urals

At least 38 sites of archaeological heritage have been recorded on the shores of Lake Tavatui. Archaeological excavations were carried out at three of the sites. The dated sites belong to the Neolithic, Eneolithic, and Early Iron Age (Chemjakin Ju, 1980; Svjatov, 2002; Bers, 2012).

The Urals region was settled by humans since the Early Palaeolithic (300–100 thousand years ago). Before the Aeneolithic dated to ~6.25–4.75 cal ka BP (Chairkina et al., 2017), the main occupation of the population in the Urals was fishing and hunting (Serikov, 1991; Lichman, 2002). An appropriating economy was associated with low population size of no more than 17.3 people/100 km^2 (Doluhanov, 1978). Cattle breeding in the forest of Urals and Trans-Urals was developed in the Bronze Age (~4.45–3.05 cal ka BP) (Molodin et al., 2014), but agriculture widely spread only since the seventieth century as a result of mass Russian colonization (Lichman, 2002). Since that time, a substantial influx of population began from the west. The Middle Urals became the centre of mining and metallurgy in the first quarter of the eighteenth century. By the end of the eighteenth century, there were 30 industrial settlements in the Urals with a population of 2–7 thousand inhabitants (Gorshkov, 1957). The forests around the metallurgical plants were cut down. The largest industrial growth in the Urals occurred during the industrialization (1928–1941) and the World War II (1939–1945). Many enterprises were evacuated from the occupied western and southern regions of the USSR to the Urals during the World War II. Currently, the total population of the Urals is more than 12 million people. Despite the increased attention to improving the ecological situation, continuous industrialization and urbanization poses a threat to the natural systems of the Middle Urals.

3. Methods

3.1. Field methods

A composite sediment core (57°13′05.85″, 60°17′98.89″), 3.5 m in length, was taken from Lake Tavatui at 7.5 m water depth with a Molchanov's bathometer for surface sediments (the uppermost 30 cm) and a Russian corer (internal diameter of 8.0 cm, length of 1 m) for the rest of the core. The core sections were extruded in the field, sliced at 2-cm intervals from the surface to 22 cm depth, and at 1–5-cm intervals to the core bottom. All samples were stored in plastic bags at 4 °C in the dark. Core description is provided in Table 2.

3.2. Laboratory analyses of water and sediments

Trace elements (Cu and Pb) concentrations in the lake sediments were determined by inductively coupled plasma-source mass spectrometry (ICP–MS) using a PerkinElmer ELAN 6000 in the Ural Electrochemical Integrated Plant. The method was described in detail by Maslennikova et al. (2020). Chemical analysis of water was carried out in the Laboratory of the South Urals Research Centre of Mineralogy and Geoecology in accordance with standard hydrochemical analysis methods (Murav'ev, 2011) listed and briefly described in the previous article (Maslennikova, 2020).

3.3. Chronology

The sediment core chronology was based on AMS ^{14}C and ^{210}Pb analyses. Two macrofossils and four organic carbon-rich bulk sediments were selected for AMS ^{14}C dating in the Radiocarbon Dating Laboratory, University of Lund, Sweden and in the Centre for Applied Isotope Studies, University of Georgia, USA (Table 3). All radiocarbon dates were calibrated using the IntCal20 calibration curve (Reimer et al., 2020). The upper sediments in the Lake Tavatui core were dated by ^{210}Pb (Table 4). Lead-210 activities were measured via ^{210}Po, assuming secular equilibrium between the two isotopes. Activities were measured with an Ortec alpha spectrometry system. ^{226}Ra used to establish supported ^{210}Pb activities was determined by gamma spectrometry. Unsupported (excess) ^{210}Pb was calculated as the difference between the total ^{210}Pb and ^{226}Ra activities. Sediment age/depth relationships were calculated using the constant rate of supply model (Appleby and Oldfield, 1978). The chronological information was integrated and modelled using the Bacon (version 2.2) software package (Blaauw and Christen, 2011) (Fig. 2).

Table 2
Description of the Lake Tavatui sediments core. Coring date: April 3, 2009, coring site coordinates: 57°13′05.85″ N, 60°17′98.89″ E.

Lithological unit	Depth (cm)	Age	Description
0	320–350	12,000–13,200 cal BP	Pale clay with blue-grey and black spots
1	310–320	11,650–12,000 cal BP	Beige clayey gyttja
2	300–310	11,150–11,650 cal BP	Brown gyttja with lightning at the bottom boundary
3	278–300	10,300–11,150 cal BP	Dark grey clastic-rich gyttja
4	0–278	2009 AD–10,300 cal BP	Organic-rich brown-olive gyttja with distinct laminations (173–176.5 cm, 6540–6460 cal BP) and black laminae (15–17 cm, 1951–1943 AD)

Table 3
AMS ^{14}C measurements of Lake Tavatui sediments. Calibrated ages are given with 95.4% probability (2¼ uncertainty).

Sample number	Depth (cm)	Laboratory number	AMS ^{14}C age (BP)	Calibrated age (cal BP)	Dated material
R407/21	65	LuS 10988	2590 ± 40	2512–2775	gyttja
R407/33	118	IGAN 5130	4080 ± 25	4445–4798	gyttja
R407/41	166	LuS 10989	5310 ± 40	5946–6264	macrofossils
R407/54	211	LuS 10990	7350 ± 45	8025–8316	gyttja
R407/66	270	LuS 10991	8950 ± 50	9907–10,227	gyttja
R407/73	302	LuS 9102	9850 ± 65	11,167–11,605	macrofossils

Table 4
^{210}Pb excess measurements and CRS ages of the Lake Tavatui core upper part.

Sample number	Depth (cm)	$^{210}Pb_{ex}$ (Bq kg^{-1})	CRS age
R 407/1	0–2	310 ± 119	2005–2009
R 407/2	2–4	289 ± 74	1999–2005
R 407/3	4–6	226 ± 77	1991–1997
R 407/5	8–10	208 ± 50	1974–1985
R 407/7	12–14	141 ± 52	1954–1965
R 407/9	16–18	104 ± 40	1913–1938
R 407/11	20–22	<38	–
R 407/13	27–29	<38	–

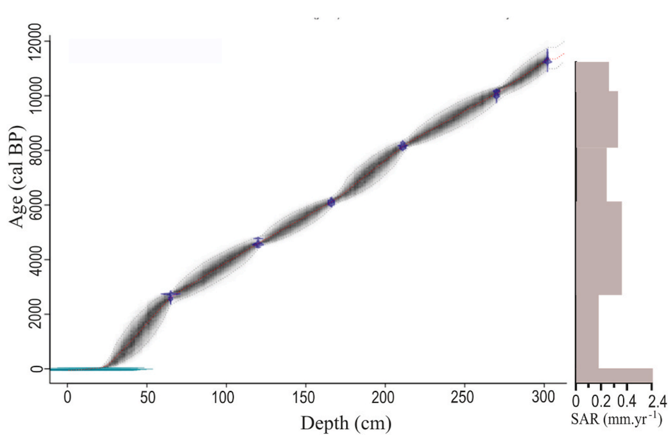

Fig. 2. Age–depth model of the Lake Tavatui sediments core produced by the Bacon software package (Blaauw and Christen, 2011) and variations of sediment accumulation rate (SAR). Grey shading indicates all likely age–depth models; grey stippled lines show 95% confidence intervals and red curve shows single 'best' model based on the weighted mean age for each depth. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. *Diatom analysis*

For diatom analysis, samples were treated with nitric and perchloric acids to remove organic matter. Slides were mounted using Elyashev's mountant (n = 1.67–1.68) (Proshkina-Lavrenko, 1974). Counting was done with a Mikmed 6 var. 7 microscope using bright-field oil immersion optics at 1000 × magnification. Measurements for taxonomic identification were carried out with ToupView 3.7. software, and photomicrographs were obtained with a ToupCAM UCMOS14000KPA digital camera. At least 500 valves were counted to determine the relative abundances in the assemblages (diatom total, percentage). Diatom identification was based on Krammer and Lange-Bertalot (1986, 1988, 1991a, b), Kulikovskiy et al. (2016), Lange-Bertalot et al. (2017), Reichardt (2018). The diatom nomenclature was updated using the online catalogue Algaebase (Guiry and Guiry, 2021).

3.5. *Numerical methods*

3.5.1. *Diatom-based inference models*

For electrical conductivity reconstructions, a transfer function developed using a 72-lake regional diatom dataset was applied (Maslennikova, 2020). For total phosphorus reconstructions, a combined TP diatom dataset from the European Diatom Database Initiative (EDDI) (Lotter, 1989; Bennion, 1994; Wunsam and Schmidt, 1995; Bennion et al., 1996a, b; Rioual, 2000) was used. Diatom-based inference models were developed by simple weighted averaging (WA) and weighted averaging partial least squares (WA–PLS) methods, using the log-transformed species relative abundance data (ter Braak and Juggins, 1993; 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 average bias, maximum bias, and coefficient of determination (r^2_{boot}) between predicted and observed values (Birks et al., 1990).

3.5.2. *EC and TP reconstructions*

The modern analogue technique (MAT) (Laird et al., 1998; Birks, 1998) was used to assess the applicability of the modern diatom assemblages to the core assemblages. Bootstrapping was used to derive $RMSEP_{boot}$ for individual EC reconstructions (Birks et al., 1990). The relative explanatory strength of EC or TP as predictors of fossil diatom assemblage composition was estimated by calculating 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 EC or TP, and λ_P is the eigenvalue of the first axis of a principal component analysis (PCA) of the same down-core diatom assemblage. The extent to which the EC or TP inference models tracked the main directions of variation in the fossil diatom assemblages was also assessed by calculation of the correlations between the DI–EC or DI–TP values in the core to the axis-1 and axis-2 scores of a PCA of the fossil diatom assemblage (Juggins, 2013; Cumming et al., 2015). Transfer functions, reconstructions, estimates of the optima and tolerances of diatom taxa with respect to EC and TP were developed using the C2 software (Juggins, 2007).

3.5.3. *Diatom and pollen relationship assessment*

The results of pollen analysis of the Lake Tavatui sediments core were described in detail in Maslennikova et al. (2016b). PCA and Pearson correlation analysis were used to explore collinearity in the set of predictor variables (spore-pollen data). The gradient lengths of the diatom data were estimated by detrended canonical correspondence analysis (DCCA) using age as the sole predictor variable to assess whether linear or unimodal techniques should be used. RDA was applied to the diatom data with a subset of relatively independent (Pearson correlation coefficient <0.7) predictor variables to assess the relationships between diatom assemblage and catchment vegetation. Sample age was partialled out as a covariable. The minimum number of independent and significant explanatory variables was identified using manual forward selection. All significance levels were determined by Monte Carlo restricted (time-series) permutation tests (1000 permutations) using CANOCO 4.5 (ter Braak and Šmilauer, 2002). A significance level of $P < 0.05$ was assumed to be significant.

3.5.4. *Diagrams and zonation scheme*

The diatom and pollen zonation schemes were developed with a stratigraphically constrained cluster analysis based on log-transformed data, with chord distance measure, using CONISS (Constrained Incremental Sums of Squares cluster analysis) in Tilia software package

(Grimm, 1991). Diagrams were constructed using C2 software (Juggins, 2007).

4. Results

4.1. Chronology

According to ^{210}Pb dating, sediment accumulation rate (SAR) for the upper 22 cm of organic-rich gyttja was 2.4 mm/year (Fig. 2). Despite the limited number of ^{14}C dates, the relatively homogeneous nature of the sediments accumulated in the pre-industrial period does not suggest major changes in the sedimentation pattern. Sediment accumulation rate in the pre-industrial period varied between 0.19 and 0.34 mm/year. Such difference between SAR of the upper part corresponding to the period of human impact and the lower part corresponding to the pre-industrial period was also observed in lakes of the Southern Urals forests (Maslennikova and Udachin, 2017; Maslennikova et al., 2018). Additional dates for the period between 2.7 cal ka BP and 1928 AD would be required to precisely investigate the observed change in SAR.

4.2. Diatom record

Altogether, 160 diatom taxa were identified in the Lake Tavatui sequence. Only one sample of clayey sediments at the core bottom (Table 2) contained the sufficient number of diatom valves for analysis. This sample (11.9–11.65 cal ka BP, core depth 315–310 cm) had a high content of oligotraphentic *Ellerbeckia arenaria* (G. Moore ex Ralfs) R.M. Crawford, 1988. In addition, *Gyrosigma attenuatum* (Kützing) Rabenhorst, 1853 which prefers alkaline water environments with moderately low to high trophic levels (Lange-Bertalot et al., 2017) is also represented in the sample in high abundance. The diatom record was divided into five zones (Figs. 3 and 4).

The first zone (DZ1, 11.65–10.1 cal ka BP, core depth – 310–271 cm) is marked by predominance of fragilarioid diatoms, especially *Staurosira construens* Ehrenberg, 1843*, Staurosira venter* (Ehrenberg) Cleve & J.D. Möller, 1879*, Pseudostaurosira brevistriata* (Grunow) D.M. Williams & Round, 1988 and *Staurosirella pinnata agg.,* which occur in water with a wide range of trophic levels and electrolyte contents (Lange-Bertalot et al., 2017 and from our observations on Urals lakes). *Punctastriata lancettula* (Schumann) P.B. Hamilton & Siver, 2008, preferring alkaline mesotrophic and eutrophic environments (Kulikovskiy et al., 2016), is also abundant. In addition, this zone is characterized by the presence of *Cymbopleura inaequalis (Ehrenberg) Krammer, 2003, Geissleria schoenfeldii* (Hustedt) Lange-Bertalot & Metzeltin, 1996, and *Navicula laterostrata* Hustedt, 1925 which are common in calcium-bicarbonate-rich waters of oligotrophic to eutrophic lakes (Kulikovskiy et al., 2016).

The second zone (DZ2, 10.1–7.9 cal ka BP, core depth – 271–208 cm) differs from DZ1 in decrease of almost all fragilarioid diatoms with the exception of *Punctastriata lancettula*, appearance and increase in *Nitzschia denticula* Grunow, 1862 and *Navicula vulpina* Kützing, 1844 inhabiting oligo- and mesotrophic calcium-bicarbonate-rich waters (Barinova et al., 2006; Lange-Bertalot et al., 2017; Kulikovskiy et al., 2016). Additionally, the second zone is marked by great variety of benthic species with wide ecological amplitude (e.g., *Navicula radiosa* Kützing, 1844*, Gogorevia exilis* (Kützing) Kulikovskiy & Kociolek, 2020) and several planktonic species *(Lindavia bodanica* (Eulenstein ex Grunow) T. Nakov, Guillory, Julius, Theriot & Alverson, 2015 and *Lindavia radiosa* agg.).

The third zone (DZ3, 7.9–3.0 cal ka BP, core depth 208–125 cm) is dominated by planktonic species represented mainly by *Aulacoseira ambigua* (Grunow) Simonsen, 1979 and low percentages of *Staurosira construens* and *Pseudostaurosira brevistriata*. *Cymbopleura inaequalis, Geissleria shoenfeldtii, Navicula laterostrata, Navicula vulpina,* and *Gogorevia exilis* disappeared. This zone is subdivided into three subzones (DZ3a, DZ3b, and DZ3c).

DZ3a (7.9–6.5 cal ka BP, core depth 208–175 cm) differs from the other subzones in high content of eutraphentic *Aulacoseira granulata* (Ehrenberg) Simonsen, 1979 and then *Belonastrum berolinense* (Lemmermann) Round & Maidana, 2001 which was found in our 72-Urals lakes database only in eutrophic lakes.

DZ3b (6.5–4.6 cal ka BP, core depth 175–125 cm) is marked by increase in benthic species including *Nitzschia denticula, Punctastriata lancettula, Stauroneis siberica (Grunow) Lange-Bertalot & Krammer, 1996*, *Navicula radiosa,* and *Pinnularia subgibba* var. *undulata* Krammer, 1992. Eutraphentic planktonic *Aulacoseira granulata* and *Belonastrum berolinense* decreased.

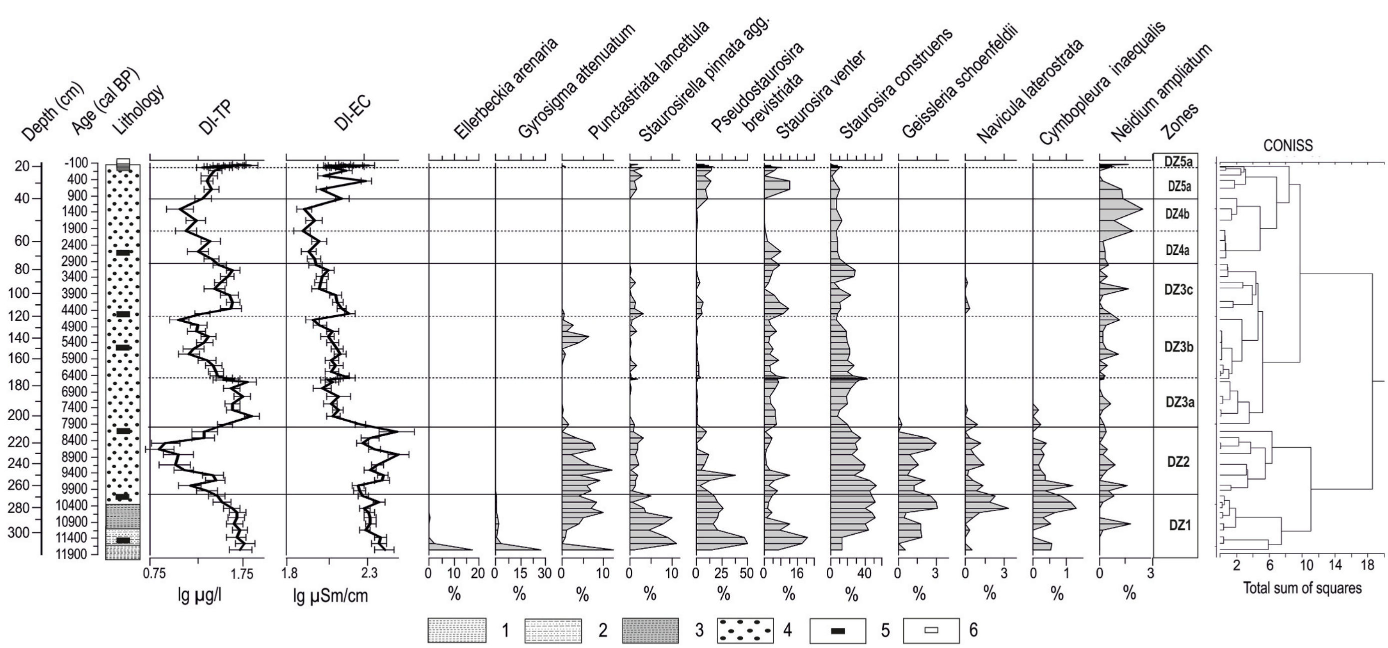

Fig. 3. Lake Tavatui diatom stratigraphy, diatom-inferred total phosphorus (DI–TP), and diatom-inferred electrical conductivity (DI–EC). Horizontal lines on DI–EC and DI–TP curves represent the sample-specific standard errors (SEB) generated using 1000 bootstrap iterations. The main lithological units (1–4) are described in Table 2. Radiocarbon-dated (AMS ^{14}C) sediment samples (5) and ^{210}Pb – dated sediment samples (6) are noted in the lithology.

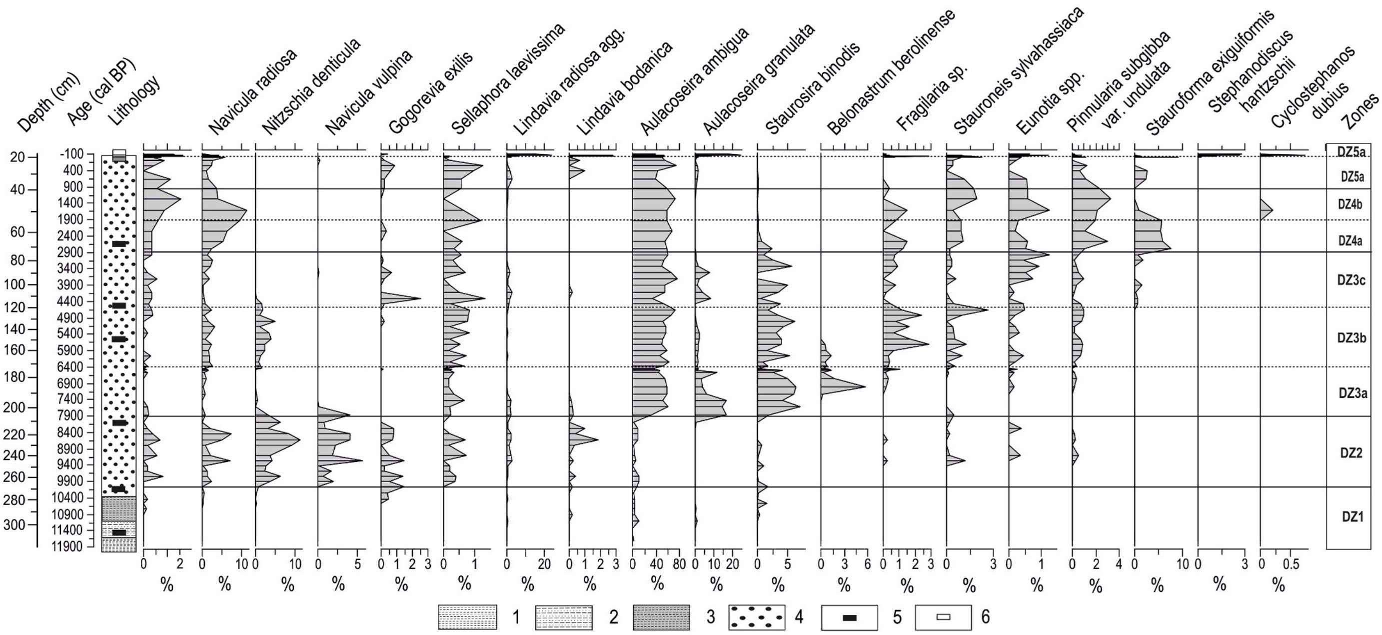

Fig. 4. Lake Tavatui diatom stratigraphy (the first part is presented in Fig. 3). The main lithological units (1–4) are described in Table 2. Radiocarbon-dated (AMS ^{14}C) sediment samples (5) and ^{210}Pb-dated sediment samples (6) are noted in the sediments core.

DZ3c (4.6–3.0 cal ka BP, core depth 125–67 cm) is characterized by a lower number *Belonastrum berolinense* and more abundant *Aulacoseira granulata* and *Lindavia radiosa* agg. Benthic *Stauroneis siberica, Nitzschia denticula, Navicula radiosa,* and *Punctastriata lancettula* became less abundant, while *Pseudostaurosira brevistriata*, *Aulacoseira ambigua, Staurosira construens,* and *S. venter* increased.

The fourth zone (DZ4, 3.0–0.95 cal ka BP, core depth 75–39 cm) includes two subzones (DZ4a and DZ4b). *Aulacoseira ambigua* was still predominant. Other planktonic species (*A. granulata, Lindavia radiosa* agg.) disappeared. Fragilarioid diatoms (especially *Staurosira binodis*) decreased. Several other benthic species preferring circumneutral or slightly acidic low electrolyte content habitats reached their maximum: *Stauroforma exiguiformis* (Lange-Bertalot) R.J. Flower, V.J. Jones & Round, 1996 in the DZ4a (2.9–1.9 cal ka BP), *Neidium ampliatum* (Ehrenberg) Krammer in Krammer & Lange-Bertalot, 1985*), Pinnularia subgibba* var. *undulata, Stauroneis phoenicenteron (Nitzsch) Ehrenberg, 1843, Stauroneis ancepsfallax* Bahls, 2010 and *S. siberica* in the DZ4b (1.9–0.95 cal ka BP).

The fifth zone (DZ5, 0.95 cal ka BP – 2009 AD, core depth 39–0 cm) is subdivided into two subzones: DZ5a and DZ5b. Fragilarioid diatoms increased mainly due to *Pseudostaurosira brevistriata, Staurosira venter,* and *Staurosirella pinnata* agg. Low EC and low pH-diatoms decreased. The abundance of *Aulacoseira ambigua* greatly varied.

DZ5b (1928–2009 AD, 19–0 cm) in comparison with DZ5a (0.95 cal ka BP – 1928 AD, 42–19 cm) is characterized by reappearance and high abundance of *Lindavia radiosa* agg. and *Aulacoseira granulata* (especially since 1956-1970 AD), presence of *Stephanodiscus hantzschii* Grunow in Cleve & Grunow, 1880*), Stephanodiscus alpinus* Hustedt in Huber-

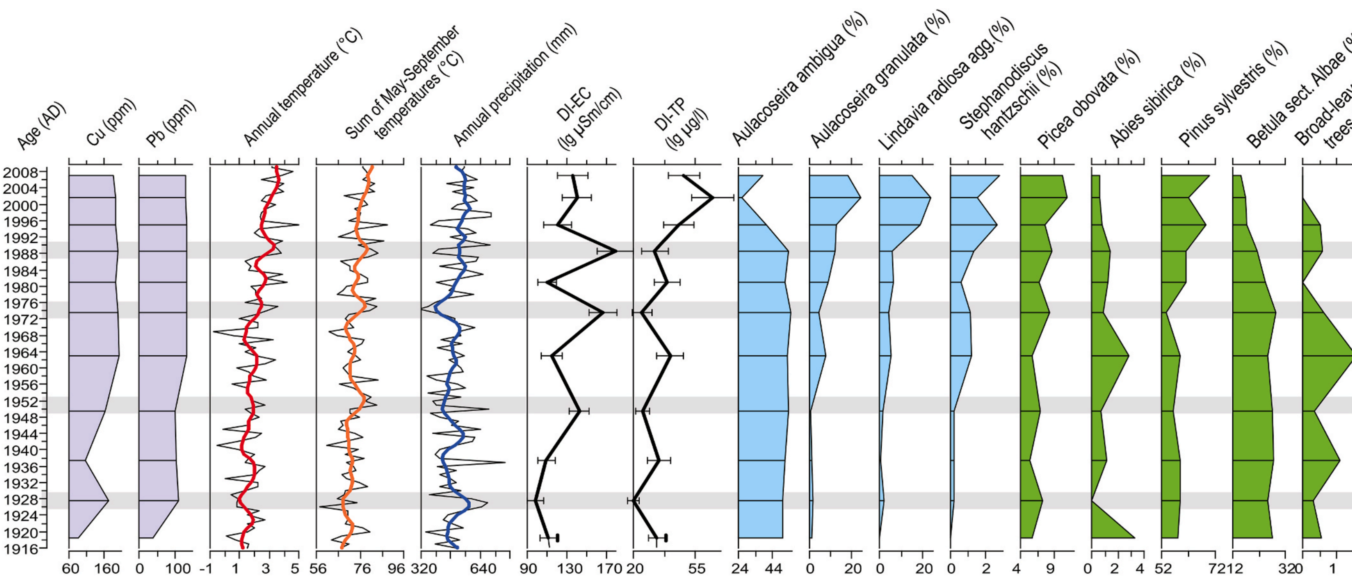

Fig. 5. Dynamic of heavy metals concentration, climate parameters, diatom-inferred total phosphorus (DI–TP), and diatom-inferred electrical conductivity (DI-EC), several diatom species (%) and pollen content (%). Climate data are from http://www.pogodaiklimat.ru/history/28440.htm. Grey strips show the periods of abnormal temperature or precipitation which are coincident with DI–EC shifts.

Pestalozzi, 1942), and *Cyclostephanos dubius* (Hustedt) Round, 1988 (since 1922–1932 AD). The highest content (3%) of *Stephanodiscus hantzschii* was observed in the sediments accumulated since the since the 1990s (Fig. 5).

4.3. Quantitative reconstructions

4.3.1. Transfer functions and quantitative reconstructions reliability

WA-PLS-C2 ($RMSEP_{boot}$ = 0.3 log μg L^{-1}, bootstrap r^2 = 0.75, maximum bootstrap bias = 0.6 log μg L^{-1}) was the best performing model for TP and WA with classical deshrinking ($RMSEP_{boot}$ = 0.2 log μS cm^{-1}, bootstrap r^2 = 0.79, maximum bootstrap bias = 0.2 log μS cm^{-1}) for EC. *Ellerbeckia arenaria* was excluded from the TP-model due to its overestimated TP-optimum (2.92 log μg/L^{-1} or 828 μg L^{-1}) obtained on the basis of TP combined dataset from EDDI (Lotter, 1989; Bennion, 1994; Wunsam and Schmidt, 1995; Bennion et al., 1996a, b; Rioual, 2000). Such a high TP-optimum contradicts literature sources (Bahls, 2012; Kulikovskiy et al., 2016; Lange-Bertalot et al., 2017) and our observations, which indicate that *Ellerbeckia arenaria* prefers sandy sediments of oligotrophic or oligo-mesotrophic freshwater habitats.

According to the MAT, only a few samples taken at the depth 220–245 cm (8.5–9.3 cal ka BP) of the Tavatui sequence had poor modern analogues in the EDDI TP-combined dataset. This is due to the absence of several species (*Punctastriata lancettula, Navicula vulpina,* and *Navicula laterostrata*) in the TP-combined dataset. All Tavatui sequence had close analogues in the Urals lakes EC-dataset.

The value of λ_R/λ_P was relatively high for EC (0.82) and low for TP (0.25). The λ_R/λ_P ratio for TP became higher (0.56) when samples of the lower part of the sequence (period between 11.9 and 6.4 cal ka BP) were removed. The diatom-inferred EC was highly correlated with the first PCA axis scores (r = 0.85). Diatom-inferred TP values were related to the third PCA axis scores (r = −0.68) and to the second PCA axis scores (r = 0.37). Correlation with the second PCA axis score increased when the samples of the sequence lower part were removed (r = 0.56). Thus, at 11.9–6.4 cal ka BP, TP had low influence on the changes in diatom assemblages. So, TP-diatom-based inference for this interval should be interpreted with caution. In the period between 6.4 cal ka BP and 2009 AD, TP became more important for diatom composition changes.

4.3.2. EC reconstructions

According to the water salinity classification based on electrical conductivity ranges (Stewart and Kantrud 1971), Lake Tavatui remained in the freshwater range throughout its history. DI–EC varied from 75 to 290 μS cm^{-1} (Table S1). Between 11.9 and 7.9 cal ka BP electrical conductivity of Lake Tavatui water ranged between 290 and 175 μS cm^{-1}. This parameter slightly decreased from 11.9 to 9.75 cal ka BP, then increased to peak values at approximately 8.8 cal ka BP, 8.1 cal ka BP while minimum values occurred at 8.65–8.3 cal ka BP. A great decrease in DI–EC values was observed at ~7.9 cal ka BP (Fig. 3). At approximately 4.5 cal ka BP, EC increased from 93 to 142 μS cm^{-1} and then decreased stepwise until 1.3 cal ka BP. The lowest EC values (75–85 μS cm^{-1}) were reconstructed for the period between 2.8 and 1.3 cal ka BP. Then EC gradually increased with variations and maxima at about 430–280 cal BP (1520–1670 AD), 1943–1956 AD, 1970–1977 AD, and 1985–1992 AD. According to the meteorological data, the DI–EC maxima at 1943–1956 AD, 1970–1977 AD, and 1985–1992 AD are coincident with the periods of low annual precipitation and abnormally high at May–September temperature (data from http://www.pogodaiklimat.ru/history/28440.htm) (Fig. 5). This regularity was especially clear during the interval 1970–1977.

4.3.3. TP reconstructions

Based on relations between TP, productivity, and DI–TP variations (7–67 μg L^{-1}), general level of Lake Tavatui productivity varied during the last 11.9 cal ka BP between oligo-mesotrophic (5–10 μg L^{-1}) and eutrophic (30–100 μg L^{-1}) (Table S1) (Wetzel, 2001).

The lake history includes the relatively high TP periods (Fig. 3, Table S1): 11.9–10.45 cal ka BP (41–56 μg L^{-1}); 7.9–6.5 cal ka BP (35–67 μg L^{-1}); 4.3–2.9 cal ka BP (30–42 μg L^{-1}); and 1914–2009 AD (32–65 μg L^{-1}) with low concentration at 1923–1932 AD (20 μg L^{-1}) coincident with lowering of annual temperature and especially the temperature for the growing season (Fig. 5). On the contrary, the lowering of TP at 1943–1956 AD (24.5 μg L^{-1}) and 1970–1977 AD (25 μg L^{-1}) was in accordance with increase in annual precipitation and decrease in temperature.

The periods of relatively low TP values included 10.1–7.9 cal ka BP with minimum at 8.65 cal ka BP (7 μg L^{-1}), 6.5–4.3 cal ka BP with minimum value at 4.7 cal ka BP (12 μg L^{-1}), and the period from approximately 2.9 cal ka BP to the beginning of the twentieth century with minimum value at 1.3 cal ka BP (12 μg L^{-1}) and the followed gradual increase.

4.4. Diatom and pollen relationship

DCCA showed a diatom species gradient length of 1.79 SD units for the first axis and 1.54 SD units for the second axis. Thus, linear ordination method (RDA) was applied (ter Braak and Prentice, 1988). The list of explanatory variables was reduced from 26 to 16 based on Pearson correlations (r > 0.7). Thus, these variables were all included in the RDA ordinations. The final RDA included the five most significant variables (P < 0.05): *Ulmus* spp., *Alnus* spp. *Pinus sylvestris* Linnaeus, 1753, and *Betula* sect. *Nanae*. The changes of these pollen types accounted for 22% of the variability in the diatom assemblages. Relationships between the diatoms and the catchment vegetation reflected in the spore-pollen data were significant as assessed by restricted Monte Carlo permutation tests. The P-value for the first and second canonical axis was of 0.002 both when using 16 or the final set of four variables. *Ulmus* spp. and *Alnus* spp. were correlated with the first RDA axis (r = 0.85 and r = 0.77). *Pinus sylvestris* and *Betula* sect. Nanae were related to the second RDA axis (r = −0.67 and r = −0.64). However, analysis of sequence reduced from 11.75 cal ka BP to 10.3 cal ka BP showed no significant relationship (P = 0.06) between the diatom assemblages and catchment vegetation. Further reduction of the sequence to 7.9 cal ka BP leaded to an even greater decrease in significance (P = 0.48).

5. Discussion

5.1. Lake ecosystem and catchment vegetation relationship

The correspondence of pollen and diatom data was expressed as the coincidence of the boundaries of diatom and pollen zones and synchronous shifts in different pollen types and diatom inferred parameters (Fig. 6). It can be associated with the simultaneous response of vegetation and the lake ecosystem to the climate change. In addition, it can be implied by the rapid response of the lake to changes in catchment caused by vegetation. A statistically significant relationship between diatom assemblages and different types of pollen was revealed only for the entire period of the lake development. The decrease and disappearance of the significance (P-value>0.05) when the sequence was reduced to 10.3 cal ka BP and 7.9 cal ka BP, shows the importance of these events in the identified relationship.

Development of coniferous forest with *Pinus sylvestris* from 10.3 cal ka BP and decrease in deciduous forest with *Betula* sect. *Albae* could lead to lowering of EC, pH, and TP with subsequent changes in lake water parameters and the composition of diatom assemblages. This is due to the fact that litter of pine forests contains less ash elements, including phosphorus, in contrast to birch forests. In addition, litter of coniferous forests takes longer to decompose (Reshetnikova, 2011). Soil solutions become more acidic and contribute to decrease in phosphorus mobility (Makarov, 2009). The development of pine forests can lead to soil podzolization and lowering of microbiological mineralization intensity (Sorokina and Sorokin, 2007). All these processes will contribute to

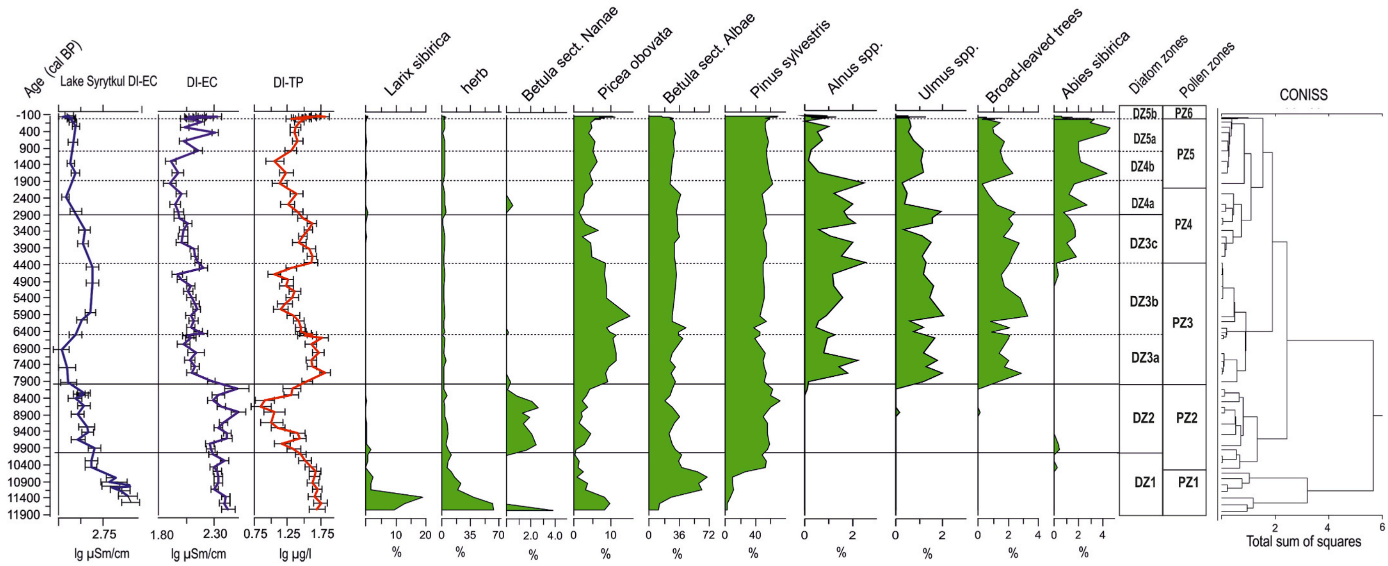

Fig. 6. Comparison between DI–TP, DI–EC, boundaries of diatom zones, pollen record of the Lake Tavatui (the Middle Urals) and DI–EC of Lake Syrytkul (the Southern Urals) (Maslennikova et al., 2016).

decrease in catchment nutrients inflow, lowering of EC and pH of the lake water. According to diatom analysis, in the period between 10.3 cal ka BP and 7.9 cal ka BP, the phosphorus content in the water decreased and oligo-mesotraphentic species appeared. Electrical conductivity of water did not decline in comparison with the previous period. However, the lowest EC values were noted for the maximum of *Pinus sylvestris*.

The influence of mixed forest with *Picea obovata*, *Ulmus* spp., *Alnus* spp. spread from 7.9 cal ka BP is more difficult to assess due to the opposite effect of these tree species on soils. Thus, the processes occurring in the soils of dark coniferous forests contribute to decrease in the total salinity of groundwater, and, consequently, to low EC and salinity of lake waters (Perel'man, 1975; Engstrom et al., 2000). At the same time, the litter of deciduous forests, in contrast to coniferous forests, is not only richer in biogenic elements, is mineralized faster, but also contains more Ca, which neutralizes acids in soils (Perel'man, 1975; Reshetnikova, 2011). EC and pH of waters become higher and catchment-driven nutrient loading into the lake increases. Alder spread could enhance nitrogen fixation in soils (Chapin et al., 1994) with a further increase in primary production in the lake ecosystem (Goldman, 1994; Hu et al., 2001). Diatom analysis showed an increase in TP, eutraphentic species, and a decrease in pH and EC. So, the lake ecosystem changes in the considered periods can be partly explained by the influence of vegetation on the lake.

5.2. Lake Tavatui development

According to quantitative and qualitative reconstructions, Lake Tavatui remained fresh throughout its development. The trophic status varied between oligo-mesotrophic and eutrophic and changed many times during the last 11.9 cal ka BP. Freshwater eutrophic carbonate-rich lake occurred from 11.65 cal ka BP became oligo-mesotrophic from 10.1 cal ka BP. The period with the highest DI–TP values (at 7.9–6.5 cal ka BP) is also characterized by great dilution in the beginning. The lowest EC was observed for the period between 2.9 and 1.3 cal ka BP, when the lake was mesotrophic again. The last period (from 1.3 cal ka BP to 2009 AD) was characterized by increase in EC and TP. So, the evolution of Lake Tavatui includes five main stages:

5.2.1. Stage 1. freshwater carbonate-rich lake (11.9–10.1 cal ka BP)

According to the diatom data, the Lake Tavatui was alkaline during the interval 11.9–11.65 cal ka BP. Diatom composition suggests that the lake was still calcium-bicarbonate-rich at 11.65–7.9 cal ka BP. EC slightly decreased after 11.75 cal ka BP, especially from 11.2 cal ka BP (Table S1). According to DI–TP, the lake was eutrophic at 11.9–10.1 cal ka BP. The diatom species of this period were mostly characterized by wide trophic tolerance with exception of *Ellerbeckia arenaria.* This species was one of the dominant diatoms at 11.9–11.65 cal ka BP. *Ellerbeckia arenaria* prefers sandy sediments of oligotrophic or oligo-mesotrophic freshwater habitats (Bahls, 2012; Kulikovskiy et al., 2016; Cantonati and Lange-Bertalot et al., 2017). It was found only in five of the 107 surveyed Urals lakes in an amount of less than 1% (our unpublished data). By contrast, *Ellerbeckia arenaria* was observed in large abundance in Lateglacial Lake Ufimskoe sediments (Maslennikova and Udachin, 2017). Exclusion of *Ellerbeckia arenaria* from the TP-model may have biased the TP reconstruction especially for the period where this species was especially abundant (11.9–11.65 cal ka BP). Thus, based on ecological preferences of *Ellerbekia arenaria* it could be concluded that during interval ~11.9–11.65 cal ka BP Lake Tavatui was less productive than 11.65–10.1 cal ka BP.

Increase in trophic status since 11.65 is likely the result of climate warming in the beginning of the Holocene. Increase in birch and lake eutrophication is often associated with human impact. The Mesolithic cultural layers (~11.95–8.45 cal ka BP) were studied and dated in Gorbunovskiy peat-bog and Shigirskiy peat-bog which located 30 and 50 km north of Lake Tavatui (Zaretskaya et al., 2014; Panova and Antipina, 2016; Chairkina et al., 2017). Mesolithic sites were also found near Lake Tavatui. However, the economy of the Mesolithic population was based on individual hunting and fishing (Serikov, 1991) not implying a substantial impact on vegetation and lake ecosystems.

5.2.2. Stage 2. freshwater carbonate-rich oligo-mesotrophic lake (10.1–7.9 cal ka BP)

The lake was still carbonate-rich. The 10.1–7.9 cal ka BP quantitative reconstruction indicates that EC slightly decreased after 10.3 cal ka BP and then increased and varied from 9.7 cal ka BP to the end of stage (Table S1). According to DI–TP, the period between 10.1 cal ka BP and 7.9 cal ka BP was marked by lower TP especially at 8.65–8.5 cal ka BP (oligo-mesotrophic lake) with slight increase at 9.6–9.4 cal ka BP (meso-eutrophic lake). The diatom assemblages for 9.3–8.5 cal ka BP have poor modern analogues in the TP-combined diatom dataset. However, known ecological preferences of diatom species (e.g., *Navicula vulpina* and *Nitzschia denticula*) also point to a lowering in the lake trophic status. This lake ecosystem changes could be associated with climate cooling or (and) expansion of pine forests with the subsequent lowering of microbiological mineralization intensity (Sorokina and Sorokin, 2007), decrease in phosphorus mobility (Makarov, 2009) and nutrients inflow.

5.2.3. Stage 3. decrease in water electrolyte content and variation in the lake trophic status from eutrophic to mesotrophic (7.9–2.9 cal ka BP)

Disappearance and decrease in the species preferring calcium-bicarbonate-rich water and DI–EC indicate that Lake Tavatui became more diluted at 7.9–2.9 cal ka BP in comparison with the previous stage. Such change could result from increase in effective moisture. In addition, decrease in EC could be forced by expansion of dark coniferous forests and podzolization in organic-rich soils reducing hydrological conductivity, groundwater recharge, and consequently the influx of base cations in groundwater inflow (Engstrom et al., 2000). The predominance of planktonic species could be explained by an increase in the lake trophic status as well as biotope changes: higher water depth and decrease in aquatic vegetation. According to DI–TP and diatom composition, the lake trophic status varied from eutrophic to mesotrophic, and three substages could be distinguished:

Substage 3.1. Eutrophic lake (7.9–6.5 cal ka BP). As follows from diatom composition and DI–TP (from 35 μg L-1 to 67 μg L-1), the lake trophic status at this substage was the highest for the entire period of pre-industrial Lake Tavatui development.

Substage 3.2. Mesotrophic lake with higher EC (6.5–4.6 cal ka BP). Alterations in diatom composition at 6.5–4.6 cal ka BP in comparison with 7.9–6.5 cal ka BP are likely related to decline in the lake trophic status. This assertion is supported by decrease in DI-TP at 6.5–4.7 cal ka BP (Table S1). The greater abundance of benthic species could also be explained by higher transparency of the lake water. DI-EC also increased.

Substage 3.3. Meso-eutrophic lake with quick lake system fluctuations (4.6–2.9 cal ka BP). The frequent change of diatom assemblages between 4.6 and 2.9 cal ka BP could be caused by quick environmental shifts partly explained by EC or pH alteration. Variations in *Aulacoseira ambiqua*, alkaliphilic species and *Eunotia* spp. are likely related to EC and pH increase (at 4.5 cal ka BP) and decrease (since 3.7 cal ka BP.). This interpretation is in accordance with DI-EC alterations: increase at 4.5 cal ka BP and then stepped decrease (at 3.7 cal ka BP, 3.0 cal ka BP) until ~1.3 cal ka BP. Changes in lake trophic status are not clearly evidenced from diatom assemblages shifts. However, based on quantitative reconstructions, it could be concluded that DI-TP was higher at ~4.3–2.9 cal ka BP than in the previous period, with only a slight decrease at 3.7 cal ka BP. The trophic status varied from mesotrophic (4.5 and 3.7 cal ka BP) to eutrophic. This change in lake ecosystem could be due to climate warming and decrease in effective moisture. Human impact could also contribute to increase in trophic status due to cattle breeding development since the Bronze Age (Molodin et al., 2014).

5.2.4. Stage 4. Low–EC mesotrophic lake (2.9–1.3 cal ka BP)

Increase in diversity and content of species preferring circumneutral or slightly acidic low electrolyte content habitats reflects decrease in lake water EC and pH at 3.0–1.3 cal ka BP. DI–EC varied from 76 to 98 μS cm^{-1}. The reasons that led to shifts in species composition with low EC and pH optimum approximately 1.9 cal ka BP are unclear. They could be related to changes in lake trophic status reflected in DI–TP gradual decrease. Such lake ecosystem change was likely associated with climate cooling and increase in effective moisture.

5.2.5. Stage 5. meso–eutrophic lake with higher TP and varied EC (1.3 cal ka BP – 2009 AD)

The shift in diatom assemblage suggests that electrolyte content and trophic status increased in comparison with the previous stage, especially in the second part of the twentieth century. These assertions are confirmed by diatom-inferred water parameters (Table S1). Despite the increased human impact since the seventeenth century, no shifts in diatom assemblages were observed. The lake eutrophication, due to increased human impact, could have been attenuated by the cool conditions of the Little Ice Age (XVI–XIXth centuries). Increase in DI–TP was observed only in the nineteenth century, when annual temperature began to rise. Sedimentary diatom assemblages from several Nothern Urals lakes show distinct changes involving planktonic diatoms in the twentieth century which is likely due to temperature increases in June and September extending a duration of the ice-free season (Solovieva et al., 2008). Lake Tavatui was also characterized by increase in several planktonic species (*Lindavia radiosa* agg., *Aulacoseira granulata, Stephanodiscus hantzschii, Stephanodiscus alpinus,* and *Cyclostephanos dubius*) from the second part of the twentieth century. This fact is in accordance with the main trend of annual temperature increase. The industrial growth in the Urals occurred from the beginning of industrialization (1928–1941) and World War II (1939–1945) could also contribute to the lake eutrophication.

Increase in DI–EC and DI–TP could be associated with climate warming and decrease in effective moisture. According to the meteorological data, the DI–EC maxima, especially at 1970–1977 AD, are coincident with the periods of low annual precipitation and abnormally high May–September temperature (data from http://www.pogodaiklimat.ru/history/28440.htm) (Fig. 5). Although the change in phosphorus content is in accordance with the main temperature increase trend, its variations were related to climate parameters in different way until and after approximately 1932–1943 AD. The lowering of DI–TP until 1932–1943 AD was coincident with marked decrease of annual temperature and increase in precipitation. The opposite relations were observed after 1932–1943 AD. In the periods of warming and decrease in precipitation DI–TP values became lower (Fig. 5). A decrease in precipitation could reduce the delivery of catchment-derived nutrients into the lake. Thus, the connection between catchment and lake, reinforced with increase in precipitation, became the main predictor explaining DI–TP variations. Such a change in the lake's response to climatic parameters could be associated with human economic activities, which contributed to increase in the content of biogenic elements in the catchment, regardless of climatic conditions.

5.3. Middle Urals palaeoenvironments

Well-dated peat and lake sediments cores of adjacent regions were used for comparison with our data (Fig. 1). Quantitative reconstructions obtained for the European part of Russia (Novenko and Olchev, 2015; Novenko et al., 2018a, b, 2019) were also considered, because the western air mass transport plays an important role in the formation of the Middle Urals climate.

5.3.1. Lateglacial–holocene transition – cold and rather dry (11.9–11.65 cal ka BP)

According to the pollen spectra (11.9–11.65 cal ka BP), the vegetation was represented mainly by herbaceous associations (*Artemisia* spp., Amaranthaceae, Poaceae, *Thalicthrum* spp.) and dwarf birch (*Betula* sect. *Nanae*) characteristic for cold conditions with relatively low effective moisture (Fig. 6). The diatom data indicating that the lake was alkaline oligotrophic or mesotrophic do not contradict this conclusion. Such conditions for the considered period were reconstructed also based on the investigation of Middle Urals peat cores (Zaretskaya et al., 2014; Panova and Antipina, 2016) and Southern Urals lacustrine sediment cores (Maslennikova et al., 2016a; Maslennikova, 2020).

5.3.2. Climate warming and slight increase in effective moisture (11.65–10.35 cal ka BP)

Decrease in herbs and spreading of trees represented mainly by spruce (*Picea obovata)* and larch (*Larix sibirica* Ledebour, *1833*) (until 11.3–11.2 cal ka BP), then, woody birch (*Betula* sect. Albae) (until 10.45 cal ka BP) could be interpreted as climate warming and increase in effective moisture. This interpretation is coincident with Middle Urals peat core-based reconstruction (Panova and Antipina, 2016) and Southern Urals forest lakes diatom records (Maslennikova, 2020).

Increase in Lake Tavatui trophic status and diatom diversity in comparison with the previous stage is likely response to the climate warming. Environmental change at 11.2 cal ka BP was reflected in Lake Tavatui pollen record (Fig. 6 and detailed discussion in Maslennikova et al., 2016b), sediments core lithology (Table 2), and pollen records of the Southern Urals (Maslennikova et al., 2016a). A slight decrease in DI-EC at 11.3–11.1 cal ka BP, according to the diatom data, is indicative of increase in effective moisture.

5.3.3. Cooling and effective moisture fluctuations (10.35–7.9 cal ka BP)

Pinus sylvestris became more important in contrast to *Betula* sect. Albae (Fig. 6). This shift in dominance could be explained by the natural forest development or slight increase in effective moisture and climate cooling. The last suggestion is also confirmed by an appearance of *Betula* sect. Nanae resistant to cool conditions. Diatom and pollen boundaries (10.1 cal ka BP and 10.45 cal ka BP) are not coincident. However, shift in vegetation at 10.45 cal ka BP is synchronous to decrease in DI–TP. The Lake Tavatui became oligo-mesotrophic. Obvious decrease in DI–EC and DI–TP at 8.65–8.45 cal ka BP is coincident with the lowest content of *Betula* sect. Albae pollen and the highest content of *Betula* sect. Nanae and *Pinus sylvestris* pollen. The Southern Urals lake sediment records also show variations in effective moisture against the general EC decrease trend. However, the main cooling trend at 10.35–7.9 cal ka BP with maximum at 8.65–8.45 cal ka BP was not recorded (Maslennikova, 2020). At the same time, the data on the southwestern part of the Western Siberian Plain (300 km to the east of studied region) suggest the humidization at 9.1–8.2 cal ka BP likely due to increase in precipitation or cooling (Ryabogina et al., 2019). Analysis of the long-term pattern of the mean annual temperature for the East European Plain reveals cooling periods at 9.3–9.1 cal ka BP and 8.5–8.1 cal ka BP (Novenko and Olchev, 2015). The transition from sapropel to peat, the absence of broad-leaved trees pollen and increase in larch pollen in the Middle Urals peat cores between 8300 ± 60 cal a BP and 7850 ± 60 cal a BP were interpreted as arid cooling (Panova and Antipina, 2016). In contrast, increase in DI–EC (at 8.1 cal ka BP) and TP (since 8.3 cal ka BP) of the Lake Tavatui water is more likely due to the climate warming also confirmed by decrease in *Betula sect.* Nanae pollen (Fig. 6). Rapid warming of the air temperature at 8.1–7.8 cal ka BP was also observed in the East European Plain (Novenko and Olchev, 2015). Small spike in DI–TP at 9.6–9.4 cal ka BP is not clearly reflected in the Lake Tavatui pollen record. However, it is almost coincident with arid warming recorded in the Middle Urals peat cores (9590 ± 40 cal a BP and 9390 ± 60 cal a BP) (Panova and Antipina, 2016). Thus, it can be concluded that the climate at 10.35–7.9 cal ka BP was cooler when compared with the previous period. Slight climate warming was noted between 9.6 and 9.4 cal ka BP and since 8.3 cal ka BP. The maximum cooling down was at 8.65–8.45 cal ka BP.

5.3.4. Warming with increase in effective moisture (7.9–6.5 cal ka BP)

The beginning of this period is coincident with the major change in the pollen and diatom records (Figs. 3 and 6). Increase in broad-leaved trees and spruce could be explained by climate warming and humidization. Diatom data reveals that the lake became more nutrient-rich again, and EC decreased dramatically. Such changes are usually related to climate warming and higher precipitation. The Southern Urals lake sediments quantitative record indicates higher effective moisture at 7.9–6.9 cal ka BP (Fig. 6; Maslennikova, 2020). Middle Urals peat core records were interpreted as humid warming from 7850 ± 60 cal BP to 6290 ± 105 cal BP (Panova and Antipina, 2016). The hydrological conditions of the Middle Urals were more stable in comparison with the adjacent area of the Western Siberia, Pre-Urals, and European Russia. The data from the southwestern part of the Western Siberian Plain were explained as warming with unstable hydrological conditions at 8.2–5.5 cal ka BP (Ryabogina et al., 2019). Mid-Kama region (Pre-Urals) vegetation reconstructions point to a dry climate at 8.8–6.9 cal ka BP and wetter climate conditions at 6.9–4.0 cal ka BP (Shumilovskikh et al., 2020). The European part of Russia was characterized by warming, however, the precipitation patterns greatly varied (Novenko et al., 2018a).

5.3.5. Cooling with slight decrease in effective moisture (6.5–4.6 cal ka BP)

The contents of spruce and broad-leaved trees pollen in Lake Tavatui sediments were more variable but not lower than in the previous period. Variation in spruce, birch, and pine at 6.5–5.5 cal ka BP could be related to climate instability at that time. Increase in broad-leaved trees at 5.9 cal ka BP and decrease at 5.0–4.7 cal ka BP could be associated with the climate warming followed by the cooling down (Fig. 6). According to the diatom data, the lake became less productive from 6.5 cal ka BP especially at 4.7 cal ka BP likely due to the warm-season cooling, while slight increase in water EC at 6.5–5.0 cal ka BP was supposed to be related to the lower annual precipitation. Thus, increase in broad-leaved trees pollen does not always assume the climate warming. At the same time, decrease in broad-leaved trees pollen associated with lowering of the lake trophic status more evidently points to the climate cooling at 5.0–4.7 cal ka BP.

EC increase since 6.5 cal ka BP of Lake Syrytkul located 200 km south of Lake Tavatui was more pronounced (Fig. 6) possibly due to lower effective moisture in the Southern Urals. The Western Siberia records were interpreted as reflecting arid phase at 7.1–5.5 cal ka BP (Ryabogina et al., 2019). The southern taiga of Central European Russia was characterized by decrease of the mean annual precipitation to modern values while the mean annual temperatures remained higher at 6.7–5.5 cal ka BP than at present (Novenko et al., 2019). The spread of spruce and broad-leaved trees in the Mid-Kama region (Pre-Urals) was interpreted as indicative of a wetter climate at 6.9–4.0 cal ka BP (Shumilovskikh et al., 2020). If only the pollen data are considered, it also should be concluded that this period was warmer and wetter in the Middle Urals than the previous one, except for 5.0–4.7 cal ka BP. However, increase in spruce and broad-leaved trees could result from their gradual spreading. Slight summer cooling and precipitation lowering at 6.5–5.0 cal ka BP could not essentially influence this process.

In contrast to rather stable EC inferred from the diatoms of Lake Tavatui sediment core, Middle Urals peat core pollen records reflect more arid conditions at 5.8 cal ka BP and 5.4 cal ka BP (Panova and Antipina, 2016). This difference may be due to a greater sensitivity of the peat record to short-term and low-amplitude climate fluctuations, whereas Lake Tavatui sediments likely reflect longer or higher amplitude fluctuations.

Variation of Lake Tavatui DI–TP confirms the climate instability of the considered period. Lowering of EC and TP at approximately 5.0–4.7 cal ka BP was coincident with the decrease in broad-leaved tree pollen and likely resulted from even more severe climate cooling. Cooling event at 5.0–4.7 cal ka BP recorded in Lake Tavatui sediments was not reflected in the Middle Urals peat cores (Panova and Antipina, 2016). However, cooling was revealed in Western Siberia at 5.5–4.9 cal ka BP (Ryabogina et al., 2019) and in Central European Russia at 5.0 cal ka BP, when the mean annual temperature was close to modern values (Novenko et al., 2018b).

5.3.6. Climate warming and instability (4.6–2.9 cal ka BP)

Decrease in spruce, increase in broad-leaved trees and fir suggest a general trend of warming and slightly lower effective moisture in comparison with the previous period. Diatom assemblages and diatom-inferred water parameters changed quickly due to the frequent environmental fluctuations. Hence, a dry warming period could be suggested at 4.6–3.7 cal ka BP and a warm season cooling at 3.7–3.55 cal ka BP. Warming and increase in precipitation began at 3.55 cal ka BP. Despite the supposed increase in effective moisture at 3.7 cal ka BP, spruce continued to decline until 2.8 cal ka BP which could be explained by the time lag of vegetation response to climate change and the complexity of interspecific relations in the forest biocenosis. At the same time, this trend in vegetation could be related to decrease in effective moisture and increase in forest fires. The last suggestion is in accordance with increase in birch, but in contradiction with our diatom data and increase in fir which, as well as spruce, is sensitive to forest fires and lowering of effective moisture. The diatom data interpretation for the period between 4.6 and 3.7 is in accordance with the pollen data.

A marked decrease in spruce pollen and broad-leaved trees in the Middle Urals peat core records was interpreted as reflecting a climate aridification and cooling at 4.2–3.8 cal ka BP (Panova and Antipina, 2016). Our pollen and diatom data confirm aridification, but contradict the cooling event at 4.2–3.8 cal ka BP which was postulated based on a decrease in broad-leaved plants pollen in Middle Urals peat cores. Broad-leaved trees pollen content in Southern Urals lakes located 20 km apart from each other give contradictory results (Maslennikova, 2020), which suggest that using the broad-leaved pollen content as the only evidence of climate warming is incorrect.

Lowering of EC since 3.8 cal ka BP was also observed in the Southern Urals forest lakes (Maslennikova, 2020). A gradual precipitation increase was recorded at ~4.9–2.8 cal ka BP, though short-term fluctuations towards dryness were also marked at 3.5–3.3 cal ka BP in Western Siberia (Ryabogina et al., 2019). However, Middle Urals peat cores pollen and botanical records showed decline of groundwater levels and growth of pines in the peatlands under moderate warm and some arid conditions at 3.8–2.8 cal ka BP (Panova and Antipina, 2016). Pollen records obtained to the east of the studied region make it possible to reveal a higher proportion of open areas in the landscape in the interval of 1700–1200 BCE (3.7–3.2 cal ka BP) (Nasonova et al., 2019). According to the palynological and sedimentological results from the Trans-Urals steppe to the southeast of the studied area, the humid climate predominated between 4.4 and 3.6 cal ka BP and became drier at 3.6–2.8 cal ka BP (Stobbe et al., 2016). Based on DI–EC, Lake Talkas located in the Southern Urals mountain forest-steppe developed under complex variations in effective moisture with slight DI–EC increase at 3.3–3.4 cal ka BP (Maslennikova, 2020). A warm and extremely dry phase was detected between 3.7 and 2.7 ka BP in the Northwest of the Mid-Russian upland (Novenko et al., 2019). In the boreal forest zone of European Russia, the relatively warm phase at 3.4–2.5 ka BP led to increase in the abundance of broad-leaved trees and the suppression of spruce. The frequency of forest fires was higher in that period (Novenko et al., 2018a). So, the Lake Tavatui diatom data at 3.7–3.0 cal ka BP contradict the effective moisture reconstructions from many regions (Stobbe et al., 2016; Nasonova et al., 2019; Novenko et al., 2019; Maslennikova, 2020), including the conclusions obtained based on the Middle Urals peat cores research (Panova and Antipina, 2016). Possible bias in DI–EC reconstruction at 3.7–3.0 cal ka BP could be associated with a growing role of nutrients or other drivers in diatom compositional changes.

Some inconsistency of the pollen and diatom data of Lake Tavatui and comparison with the records of adjacent regions complicates the interpretation of effective moisture change at 3.7–3.0 cal ka BP, although it can be unambiguously asserted that the climate warmed at 4.6–3.0 cal ka BP relative to the previous period.

5.3.7. Climate cooling and increase in effective moisture (2.9–1.3 cal ka BP)

Spruce became more abundant from 2.8 cal ka and broad-leaved trees, especially *Ulmus* spp., became rarer at 2.8–1.9 cal ka BP. From 1.9 cal ka BP, pine, broad-leaved trees, and fir increased and birch decreased. Such changes could be explained by climate cooling at 2.8–1.9 cal ka BP and warming at 1.9–1.3 cal ka BP. DI–TP decreased, and DI–EC continued to decrease, benthic diatoms preferring low electrolyte content habitats increased from 3.9 cal ka BP. The shift in diatom assemblage at 1.9 cal ka BP was expressed only as replacement of some low-EC and low-pH species by others. So, the diatom data are indicative of the climate cooling and higher effective moisture at 2.9–1.3 cal ka BP. Such climate changes were also reflected in adjacent regions. Decrease in DI–EC at 2.8 cal ka BP was observed to the south of Lake Tavatui, especially in Lake Talkas located in the forest-steppe zone of the Urals mountains (Maslennikova, 2020). Palynological and sedimentological results from the Trans-Urals steppe to the southeast of the studied area revealed that humid climate was predominant between 2.6 and 1.4 cal ka BP (Stobbe et al., 2016). Western Siberia is characterized by considerable increase in humidity and cooling since 2.8 cal ka BP (Nasonova et al., 2019; Ryabogina et al., 2019). The climate in the Mid-Russian Upland during the period of 2.7–2.0 ka BP became cooler and wetter (Novenko et al., 2019).

5.3.8. Decrease in effective moisture (from 1.3 cal ka BP to 1928 AD)

Pollen spectra remained almost unchanged in comparison with the period between 1.9 and 1.3 cal ka BP. The exception was decrease in *Ulmus* spp. at 0.7 cal ka BP. The pollen data from Northern Urals suggested the climate cooling and decrease in effective moisture from 0.7 cal ka BP (Antipina et al., 2014). However, as follows from diatom composition and diatom-inferred parameters, the Lake Tavatui trophic status and water electrolyte content increased markedly. In the Southern Urals lakes, water EC continued to decrease (Lakes Talkas and Ufimskoe) or remained unchanged (Lake Syrytkul) (Maslennikova, 2020). Thus, if only the Lake Tavatui diatom analysis data are taken into account, the climate warming, especially in the growing season, and decrease in effective moisture compared with 1.9–1.3 cal ka BP can be assumed. Questionable results could be due to the influence of some local factors, such as human impact on lake parameters (DI–TP, DI–EC). It is necessary to obtain additional radiocarbon dating of the lake sediments accumulated at this time and archaeological studies are required to assess human impact on the lake in this period.

5.3.9. Climate warming (1928–2009 AD)

Spruce and pine increased in contrast to fir, birch, and broad-leaved trees. The pollen record indicates a higher effective moisture and winter-spring cooling. According to the meteorological data, annual temperature, especially in winter and spring, increased. The beginning of the considered period is coincident with the industrialization at 1928 AD. This period was characterized not only by an increase in heavy metal concentrations (Fig. 5), but intensification of human-induced deforestation. Thus, pollen-based climate reconstructions need to be evaluated carefully, as these could be biased. The diatom response is in accordance with the main trend of increase in annual temperature, despite possibly human-induced variations in water phosphorus content.

6. Conclusions

Comparison of the diatom analysis data with palynological proxies made it possible to evaluate environmental changes in the Middle Urals over the past 11.9 cal ka BP. Diatom and pollen records reflect cold and rather dry conditions at 11.9–11.65 cal ka BP. Climate warming and slight increase in effective moisture between 11.65 and 10.35 cal ka BP was followed by cooling at 10.35–7.9 cal ka BP with the maximum cooling down at 8.65–8.45 cal ka BP, effective moisture variations at 9.7–7.9 cal ka BP, slight warming at 9.6–9.4 cal ka BP, warming and decrease in effective moisture since 8.3 cal ka BP. The warming with a great increase in effective moisture at 7.9–6.5 cal ka BP was followed by the cooling at 6.5–4.6 cal ka BP, climate warming and instability at 4.6–3.0 cal ka BP. Cooling and increase in effective moisture continued from approximately 3.0–2.8 cal ka BP to 1.3 cal ka BP. Despite the difficulties in comparing the data obtained by different methods, it could be concluded that environmental changes revealed for the Middle Urals were partly reflected in the Southern Urals, Pre-Urals, Trans-Urals, Western Siberian Plain, and East European Plain palaeorecords. Climate warming at 8.3–7.9 cal ka BP and increase in effective moisture at 3.0–2.8 cal ka BP were especially well-recognized (Novenko and Olchev, 2015; Stobbe et al., 2016; Panova and Antipina, 2016; Novenko et al., 2018a, 2019; Ryabogina et al., 2019; Nasonova et al., 2019; Maslennikova, 2020).

Five main stages in the development of Lake Tavatui can be identified on the basis of the diatom record. Based on quantitative reconstructions, it could be concluded that Lake Tavatui remained in the freshwater range throughout the 11.9 cal ka BP covered by the sequence with trophic status varied between oligo-mesotrophic and eutrophic. The highest DI–TP values were observed for the period between 7.9 and 6.5 cal ka BP and since the 1990s.

Until the mid-twentieth century, the lake ecosystem shifts could be explained by natural factors, i.e. direct and catchment-mediated climate impact. The change in phosphorus content was in accordance with the temperature increase since the mid-ninetieth century. However, after 1932–1943 AD, the periods of warming and decrease in precipitation resulted in lowering of DI–TP, possibly due to reduction of delivery of catchment-derived nutrients into the lake. This change in the lake ecosystem response to climatic parameters could be associated with human impact, which contributed to nutrients content in the catchment, regardless of climatic conditions.

Author contributions

The sole author of this paper defined the research goals, performed the diatom, pollen and statistical analyses and synthesized the data, conducting all the research and investigation processes, wrote the paper and acquired the financial support.

Data availability

Fossil collections presented in this manuscript are kept at the South Urals Research Center of Mineralogy and Geoecology, Urals Branch, Russian Academy of Sciences (Miass, Russia) and are available on request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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