Late Glacial and Holocene in the south of Western Siberia: geochemical indices and pollen data in Kyrtyma Lake sediments

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Abstract. This paper presents some conclusions of a study of a long-term lake sequence in the southwestern part of the Western Siberian Plain. Environment changes in the Holocene were identified according to geochemical indices, accumulation rate, plant macrofossils, and pollen data of sediment in Lake Kyrtyma. As a result, we firstly obtained the data on climatically conditioned changes of the sedimentation in the flat part of Western Siberia over at least the last 15 thousand years. Geochemical changes in the sediment properties clearly revealed climate change over the Late Glacial and the Holocene. Changes in the composition of macrophytes gave little independent information, while the pollen data are perfectly combined with the sedimentation features and serve as a reliable source for the reconstruction of vegetation changes and landscape. The transition to the Holocene was marked at about ∼12–11.2 ka BP, subsequent ongoing warming led to the aridest Holocene phase at ∼7.1–5.5 ka BP. Cooling and the resulting decrease in vaporation began at ∼5.5–4.9 ka BP, but a cardinal shift in sedimentation due to a gradual increase in precipitation was at ∼4.9–2.8 ka BP. The most significant increase in humidification and a cooling began at 2.8 ka BP.

1. Introduction

Peat deposits are predominantly used in Western Siberia as a main source for the reconstruction of the Holocene environment and vegetation history, but the age of peatlands in the southern part of Western Siberia rarely exceeds 4500 years [1]. Studies of lacustrine sediments and their proxy as a high-resolution paleocological records in the south of Western Siberia have a relatively short history [2-6] and the results from previous studies essentially cover the second half of the Holocene and give critically little information about the Early Holocene. For the lowland part of Western Siberia, only some sites in the Ob river basin – peatlands with lake deposits in the bottom, provided information on the boundary between the Late Glacial and the Early Holocene [7-9]. Basically, full long-term lake sequences were obtained only in the Ural and Altai mountains [10-14]. The location of such natural archives in the mountains undoubtedly reflects climate changes of the global rank, but the high altitude effect suggests that the slopes catch much more precipitation than the flat territories, and the pollen data is always complicated to analyze due to altitudinal zonality. Therefore, conclusions about the intensity of changes in the temperature regime, humidification and the history of vegetation obtained in the mountainous regions of the Urals and Altai cannot be directly extrapolated to vast flat areas of...
Western Siberia. Thus, natural archives that would reflect the changes in the landscapes of the entire Holocene and the Late-glacial at the plain's location are necessary for further research.

We are also interested in studying lake sediments in the south of Western Siberia due to the influence of the dynamics of climate on the settlement history and human activity in antiquity. The migration routes of the ancient population from all directions intersect in the south of Western Siberia, and archaeological data illustrate the compelling history of cultural processes and changes in the economy in the forest-steppe contact zone. Paleoecological archives of the lake can provide unique detailed information about the habitat features and the impact of human activity on the landscape transformation.

2. Key studies
Lake Kyrtyma is located in the south-western part of the West Siberian Plain near the large lake system of Andreevskoe in the Tura-Pyshma interfluvе. Individual shallow lakes, complex lake systems, and wetlands appeared here between the old sand dunes. The shape of the lakes, their area, banks and presence/absence of runoff from these lakes can dramatically change even in case of insignificant fluctuations in humidity. It explains the different altitude positions of more than 360 multi-period archaeological sites in the area [15].

Kyrtyma is a small isolated freshwater lake located to the south of the large flowing Andreevskoe Lake System (56.990 N, 65.830 E), with dimensions of 1x0.35 km and about 1.5 m in depth (figure 1). Such shallow water lakes of Western Siberia are characterized by a deficit of oxygen during the winter ice period and accumulation of predominantly sapropelic organic matter. The main catchment rocks are the Late Quaternary sandy thin-layer sediments, their thickness varies from 5 to 30m depending on the erosional surface. Sand dunes and river terraces in the Tura-Pyshma interfluvе are occupied by pine forests, which are interspersed with birch groves, swamps, and different types of meadows. The study area is located in the subtaiga (the south part of the taiga belt with birch-pine forests). It is an ecotone between the humid and arid zones in Western Siberia, and it is very sensitive to climatic shifts, especially changes in humidity.

Figure 1. Location of Kyrtyma Lake in the Andreevskoe lake system (a); the study area and natural zonality in the south of Western Siberia (b); view of Kyrtyma Lake (c).

3. Methods
3.1. Coring
The lacustrine sediments of Lake Kyrtyma were drilled with a Bijker piston sampler (Eijkelkamp) in winter from the ice. A complete sediment column of 472 cm was obtained from six cores with an
undisturbed structure. As there is always a sediment loss or disturbance at the lower end of each core section, each core has a 10 cm overlapping end section. At the lab, we cut the overlapping parts to provide an undisturbed sedimentological sequence, which was used for analyses and dating.

3.2. Chronology and accumulation rate
The AMS $^{14}$C dating of the lake and peat samples was performed in the NTU AMS Lab at the National Taiwan University with a 1.0 MV Tandetron Model 4110 BO-Accelerator Mass Spectrometer. We used chronology package Bchron (figure 3) in R software environment [16] that enables age-depth modelling as per the algorithm [17] to construct the age-depth relationship and to determine the accumulation rate. In all calculations and constructions, Intcal 13 calibration curve was used in Bchron package. The result of mean accumulation rates at every cm depth was also calculated in Bchron.

3.3. Geochemical analysis
In total, 42 geochemical samples were taken from all layers of the Kyrtyma lake core. The contents of macro- and microelements in the sediments were determined on a SPECTROSCAN MAKS-GV X-ray device. In total, 36 elements and compounds were analysed. Total carbon and nitrogen were carried out by dry combustion in an oxygen flow on an element automatic C/N analyser Vario ELIII.

As Kyrtyma is a small closed lake and the final receiver of the flow-off basin, the lake deposits reflect the geochemical features of the surrounding landscapes and in-lake sedimentation conditions. To analyse such changes along the profile, we tried to apply the following geochemical ratios [18-24]: Al$_2$O$_3$/(CaO + Na$_2$O + K$_2$O + MgO), Rb/Sr, Zr/Rb, Ti/Zr – weathering ratios, associated with granulometric composition or homogeneity of the material; (CaO + MgO)/Al$_2$O$_3$ – calcification ratio; Ba/Sr – hydrothermal index; Na$_2$O/Al$_2$O$_3$ – salinization ratio; (Fe$_2$O$_3$+MnO)/Al$_2$O$_3$ – oxidation ratio; C/N – ratio indicating the composition of organic matter; Ti + V + Cr + Zr + Ga – the sum of elements-hydrolyzates.

3.4. Analysis of plant macrofossils and pollen
Twenty-eight 1–2 cm thick samples for macro remains analysis were taken from the Kyrtyma core from all layers of the sediments. Seeds and soft plant tissues were extracted by wet sieving of the sediments with a 250-μm cell sieve.

In total, 472 palynological samples from each centimeter of the sediments were selected to obtain high-resolution information. Each sediment sample was processed following standard palynology methods: HCl, KOH, HF, and sifting. The counts of pollen, charcoal, and NPP in each sample have not been fully completed yet, however, we are now able to operate preliminary pollen results (with an interval of 10 cm) of the count in the profile and build first conclusions.

4. Results

4.1. Stratigraphy, chronology and accumulation rates
The analysis of the age, stratigraphy and accumulation rates, changes in the geochemical composition and preserved plant macrofossils in Lake Kyrtyma allowed us to identify changes in the sedimentation and environmental development in the Late Glacial and the Holocene [25].

The distribution of 15 AMS dates in the age-depth model (figure 2) shows a consistent accumulation of silt and gittia. The remains of macrophytes, even in the lower part of the profile, prove that aquatic accumulation of sediments has not been interrupted since the Late Glacial, although the sedimentation rate varied from 16 to 84 years/cm.

Kyrtyma Lake allows us to reconstruct decadal-to-centennial events if we explore every centimeter of the sediments. The lowest part of the profile with silt and loam deposits (below 365 cm depth, see table 1) is associated with the Late Glacial. The rise in the accumulation curve at 360 cm depth was reliably dated to 11.2 ka cal yr BP, when organic gittja began to accumulate, its deposition from 360 to 134 cm was relatively stable and fluctuated about 0.03 cm/yr. The most rapid accumulation rate (up to
15 yr per cm) corresponds to the dark gray-brown layer at 273–250 cm accumulated about 8.6–8.2 ka cal yr BP. Also, a short increase in the accumulation rate to 0.04 cm/yr at the 217–208 cm interval occurred 7.3–7.1 ka cal yr BP but it is not reflected in the stratigraphy. A long period of rapid sediment growth (0.05–0.04 cm/yr) happened at about 4.8–2.8 ka cal yr BP. A sharp and significant decrease in the accumulation rate (up to 0.01 cm/yr or 84 yr per cm) took place in the upper 33 cm in the last 2.8 ka cal yr BP and corresponded to the slow sedimentation rate of 84 yr per cm.

Table 1. Lithological description of the Lake Kyrtyma sediments.

| Depth, cm | Sediment type   | Description                                                                 |
|----------|-----------------|-----------------------------------------------------------------------------|
| 0-360    | Organic-rich gytja | 0-101 cm organic-rich dark brown homogenous layer, 101-143 cm light brown layer, 143-179 cm dark olive layer, 179-215 cm light olive layer, 215-236 cm dark gray-olive layer with ostracods, 236-247 cm light gray-brown layer, 247-270 cm dark gray-brown layer, 270-310 cm light gray-olive layer, 310-325 cm dark gray layer, 325-360 cm gray layer |
| 360-376  | Organic-clayey gytja | Dense black organic-clayey layer with a huge number of ostracod shells differs sharply from lower sediments |
| 376-472  | Silt             | It has low content of organic matter, interlayers: 472-454 cm light brown-grey silt, 454-417 cm light grey-olive silt with rusty coloured spots, 417-376 cm light grey-brown silt |
| below 472| Loam             | Light grey, with admixture of coarse sand                                    |

Figure 2. Age-depth model and accumulation rate of the Kyrtyma Lake sediment sequence.

4.2. Geochemical data
According to the geochemical changes, the Kyrtyma Lake sediments are divided into four parts (figure 3):
I. Silicate silt deposits in the lowest part in the 450-420 cm interval (before 11.2 ka cal yr BP) associated with maximum amounts of SiO2 (up to 48%), Al2O3 (up to 9.75%), S (up to 1.1%), increased amounts of elements-hydrolyzates TiO2, V, Cr, Zr, Ga, and maximal values of the
weathering ratio Al2O3/(CaO + Na2O + K2O + MgO). These sediments are characterised by a low carbon level (about 5%) and a very high C/N ratio (varies abruptly from 20 to 70), which mainly indicates the terrestrial origin of the organic matter.

Figure 3. Changes of the geochemical markers of the Kyrtyma Lake sediments.

II. Carbonate gittja are presented in the interval of 370-143 cm (11.2–4.9 ka cal yr BP), with a sharp decrease in the content of SiO2, Al2O3, Fe2O3 and the minimal portion of elements-hydrolyzates and weathering ratios. Another feature is significantly increased calcification ratio (CaO + MgO)/Al2O3 and salinization ratio Na2O/Al2O3, which show peak values around 11.2, 9.2 and 6.3 ka cal yr BP. Ba/Sr ratio shows the minimum because of high strontium.

III. The interval of 143-56 cm (4.9–3.3 ka cal yr BP) is a transition from carbonate to silicate-carbonate gittja. Gradual changes of all geochemical parameters are recorded for 4.9–4.4 ka cal yr BP, but sharp fluctuations of all ratios occur at 3.8–3.3 ka cal yr BP, indicating repeated environmental changes. In general, the salinization, calcification and oxidation ratios decrease, and the weathering coefficients increase. Elements-hydrolyzates were also determined more actively flowing into the lake with the surface runoff. As a part of the organic matter, the nitrogen content also sharply increases 4.4–3.7 ka cal yr BP, but then significantly decreases about 3.5-3 ka cal yr BP.

IV. For the upper 53 cm (starting from 3.3 ka cal yr BP), the geochemical data indicate increased input of terrigenous material. The primary evidence of this is an increase in elements-hydrolyzates in the gittja. The weathering ratios increase substantially, the Fe2O3 content increases (up to 7%), but CaO, MgO and C/N ratio all decrease to their minimum values within the whole record. The increase in P2O5 content to 1.5% and S to 0.78% (not shown on the charts) in the upper sample (last 300-250 years) is associated with anthropogenic activity in this area in the late Middle Ages and recent times.

4.3. Composition of macrophytes
In the shallow-water Kyrtyma lake sediment, macrophytes contribute most to gittja formation, soft tissues of plants are mostly found. Most macrophytes found are eurybionts; however, some taxa are associated with certain types of sediment. The abundance of submerged \textit{(Ceratophyllum L.)} and floating-leaved \textit{(Nuphar Sibth. & Sm., Stratoideae aloides L.)} hydrophytes are confined to layers of carbonate or silicate-carbonate gittja. Helophytes \textit{(Phragmites Adans., Carex L., Bryales)} appear mostly in the lower part of the profile in the silicate silt layers; charcoals are most common in this layer, which indicates a greater transferal of terrestrial material into the lake basin.

4.4. Pollen analyses
Changes in the pollen composition are well-pronounced and reveal significant changes in vegetation between the Late Glacial and the Holocene. Herbs pollen dominates in the lower part of the Kyrtyma sequence, and it is very quickly replaced by a tree pollen domination interval above 360 cm. In general, the time around 15.5-14.0 ka cal yr BP is consistent with Chenopodiaceae, \textit{Artemisia} and Poaceae zone; a short interval at 13.9-13.4 ka cal yr BP shows an absolute predominance of \textit{Chenopodiaceae}; Poaceae zone with wormwood and short appearance of spruce pollen peak falls on the interval from 13.0 to 12.1 ka cal yr BP.

Around 12.1-11.2 ka cal yr BP, a rise of the \textit{Betula} pollen curve begins; it is a pronounced dominant in the sediment associated with the beginning of the Holocene. However, around 9.6 ka cal yr BP \textit{Pinus} pollen is also abundant in sediments along with birch, while the curves of these two main forest-forming species are usually in the antiphase. The zone of the highest prevalence of pine pollen was established at about 8.0–6.0 ka cal yr BP; the maximum of birch pollen was indicated in a period of 4.0–0.5 ka cal yr BP.

5. Discussion
Sediments with a low content of organic material and very high rates of weathering coefficients accumulated around 15.5–13.7 ka cal yr BP. They correspond to a cold climate. The lack of moisture allowed only open steppe landscapes with xerophytes and halophytes vegetation to exist, although local birch forests could remain near in depressions. The extremely dry conditions for a short time of 13.9-13.4 ka cal yr BP are marked by the abundance of \textit{Chenopodiaceae}, apparently, the surrounding landscapes took the form of cold semi-deserts at that time. Thus, the Bøllinge-Allerød chronozone [26] is manifested as the most continental time with open landscapes of cold steppes (tundra-steppes?).

Further changes are associated with moderately dry conditions and with grass-wormwood vegetation around 13-12.1 ka cal yr BP. An increase in moisture probably occurred at 12.5 ka cal yr BP and appeared as spruce-birch woodlands surrounded by the grassy steppe. Conditions for intensive transfer of mineral particles from the catchment area were created due to the prevalence of open landscapes and a lack of forests, similar conditions were identified for the Late-glacial period from the Ural lakes [26-28].

Black gittia deposits, enriched in organic matter with an abundance of ostracods, accumulated 12.1–11.2 ka cal yr BP, and mark a sharp reorganization of all geochemical parameters and the landscape appearance. This transition occurs at the boundary between the Younger Dryas and the Holocene about 11.7 ka cal yr BP [25]. Sedimentation changed substantially from predominantly mineral to organic, warming led to an increase in precipitation and raised groundwater levels. The proportion of birch forests is gradually increasing although meadow steppes prevail in the landscape. An intensive birch forest expansion continued in the Preboreal period about 11.2-10.1 ka cal yr BP, however, geochemical markers also revealed an episode of short-term cooling of 10.5 ka cal yr BP. This time was appeared chilly, but also humid, in contrast to the lakes of the southern Urals, where 11,300–11,000 a BP was a cold and drier phase [26].

Subsequent changes in sedimentation indicate general warming and an unstable hydrological regime of the lake. Pine forests began to play an important role in vegetation about 9.6 ka cal yr BP apparently spreading from the Urals refugium. As a rule, the pine/birch ratio in the forest composition reflects the humidification, i.e the proportion of birch forests increases in more humid periods with...
water table elevations, but pine displaces birch during dry periods. The geochemical markers indicate an increase in the moisture content at about 8.2 ka cal yr BP and an increasing role of birch forests at that time. The driest phase of the Holocene is explicitly recorded in the lake sediment of about 7.1–5.5 ka cal yr BP (the minimum values of the weathering ratio and the maximum of calcification, salinization and oxidation ratio), and indicates aridization. The intensive oxidation at that stage was associated with a high biological activity of macrophytes, that overgrew in the lake (Nuphar, Najas, and Stratiotes aloides), and with dystrophy of the reservoir due to warm weather. A sharp increase in the share of cow lily, against the disappearance of pondweed and hornweed, suggests a critical decrease of the water level, but the lake did not desiccate completely. The pollen data showed an expansion of pine forests, adverse conditions for small-leaved forests, but it did not reveal unambiguous signs of the increase in the share of meadow-steppe plots in landscapes.

During the period from 5.5 to 4.9 ka cal yr BP, all indicators of arid conditions are reduced. However, the water level was probably still low because the markers of sandy fractions, the weathering ratios, and accumulation rate insignificantly increased. It is highly likely that evaporability decreased at that time due to lower summer temperatures, but we don't see evidence of a significant increase in precipitation. Nevertheless, the aquatic Kyrtyma vegetation was already restored, and pondweed, which had almost disappeared from the macrophyte community in the previous arid phase, appeared again. The decrease in the Kirtyma Lake level is consistent with Baraba, where significant warming occurred around 7.5–5.5 ka cal yr BP [29]. The climatic optimum in the Ural lakes was marked at 7.4–6.3 ka cal yr BP and was described not only as warm but also as rather humid [26]. Rising lake levels is well pronounced in the Middle Urals, but the southernmost (Ufimskoe Lake) shows a decrease similar to Kyrtyma Lake.

The lake environment considerably changed around 4.9 ka cal yr BP, when a significant increase in the accumulation rate occurred. Apparently, the lake level gradually rose due to increasing rainfall. Simultaneously with those processes, the role of birch in the forests increased again, constantly with the participation of spruce, while the proportion of pine decreased. Cooling also began at 5.5 ka cal yr BP in the east of the West Siberian Plain [29], although climate deterioration in the south of the Ural Mountains started earlier around 6.3 ka cal yr BP [24].

However, humid conditions were not constant, there was also an opposite impulse towards dryness at about 3.5–3.3 ka cal yr BP. Although, the main trend of humidification continued at 3.2–2.8 ka cal yr BP, as can be seen from the presence of insoluble minerals, clay particles, and decreased carbonates – all of which indicated sedimentation against an increase in the depth of the lake. A significant increase in surface runoff, an increase in weathering ratio and hydrothermal index, low C/N and calcification ratio in sediments younger 2.8 ka cal yr BP are associated with increasing humidity and cooling. Intensive displacement of pine forest and dissemination of birch, which had lasted until the last 500 years, also occurred in that period. Our conclusions contradict the diatoms data from Kulunda in the southeast of the West Siberian Plain (Bolshoye Yarovoe Lake [31]), since the greatest shallowing was precisely 3950–1920 cal yr BP in the steppe lakes there (Lake Bolshoe Toroki [30]). However, in the forest-steppe of Baraba, the beginning of the deep-water stage in the development of the lake was marked after 3.6 ka cal yr BP (Malye Chany [28]).

6. Conclusion
Lake Kyrtyma located in the south-west of Western Siberia is a unique continuous paleoecological archive, rare in age, completeness, resolution, and preservation of the last 15 ka cal yr BP. It is important that new data obtained reflects changes in the flat area on the border of the modern humid and arid zones in Western Siberia, and that these data do not have a high-altitude complication. It was established that geochemical features and pollen record of the lake sediments are very sensitive to climate-related environmental changes and allowed us to identify well-known global climatic events and also to extract regional nuances in the landscape development in the Holocene.

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