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Magnetic properties of lake Bannoe sediments (Southern Urals, Russia)

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Abstract. ***Relevance.*** Lake sediments contain the unique data on mineral composition and physical properties reflecting environmental and climate changes over the past millennia. These data are extremely important for understanding the environmental processes today and in the future. Magnetic minerals and properties are considered as essential to reconstruct sediment supply and climate fluctuations. ***Aim.*** To reveal magnetic susceptibility and coercive spectrometric parameters as relevant for lake cores stratification in accordance with climate terms. ***Object.*** Core of Lake Bannoe sediments (length is 512 cm). The age of the core is ~12.5 thousand years old. ***Materials and methods.*** The magnetic susceptibility was measured using MFK-1A Kappabridge (AGICO). The hysteresis parameters of the studied sedimentary deposits were determined using a coercive spectrometer (J_meter). Induced magnetization based differential thermomagnetic analysis was performed on an auto-registering magnetic torsion balance using the zero method. ***Results.*** The magnetic susceptibility of sediments taken from Lake Bannoe ranges from 0.88 to 7,87·10^{-7} m^3/kg. Differential thermomagnetic analysis revealed the presence of magnetite in these sediments. The Day–Dunlop plot indicated that the magnetic grains in the samples of Lake Bannoe are a mix of single-domain and multi-domain (pseudo-single-domain) particles, with multi-domain grains comprising 70 to 92% of the total. Variations in magnetic susceptibility and its components were analyzed in relation to the Holocene climatic stages as defined by the Blytt–Sernander classification. ***Conclusions.*** It is found that the variations in magnetic properties of the studied sediments are in harmony with climate stages of the Holocene. Sediments of Lake Bannoe recorded the Bond event #8 (~11100 years ago), as well as regional aridization events which occurred ~4500 and ~2000 years ago. The results obtained during this study complement already existing paleoclimatology data, which will be interesting to a wide range of researchers – from paleoclimatologists to limnologists and ecologists.

Keywords: magnetic study, paleoclimate, lacustrine sediments, Holocene, conditions of sedimentation

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Магнитные свойства донных отложений озера Банное (Южный Урал, Россия)

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Аннотация. ***Актуальность.*** Известно, что вариации магнитных свойств донных отложений современных озер отражают условия окружающей среды: интенсивность поступления осадочного материала в бассейн седиментации, характер источников осадочного материала, колебания уровня озера, климат и другие условия озерного осадконакопления. Методики измерения параметров магнитных свойств отличаются относительной простотой и оперативностью, что делает их весьма удобным инструментом для детальной фиксации изменчивости свойств донных отложений озер, дальнейшего выявления сигналов и трендов изменений условий осадконакопления, расчленения и сопоставления озерных осадочных разрезов. ***Цель:*** изучение магнитно-минералогических свойств осадочных отложений озера Банное. ***Объект.*** Керн донных отложений озера Банное длиной 512 см, возраст которых составляет не менее 12,5 тыс. к.л.н. ***Методы.*** Магнитная восприимчивость получена с использованием MFK1 A Kappabridge (AGICO). Гистерезисные параметры исследуемых осадочных отложений были определены с помощью коэрцитивного спектрометра (J_meter). Дифференциальный термомагнитный анализ образцов по индуцированной намагниченности был выполнен на авторегистрирующих крутильных магнитных весах, действующих по нулевому методу. ***Результаты.*** Значения магнитной восприимчивости осадков озера Банное изменяются в диапазоне (0,88–7,87)·10^{-7} м^3/кг, озера. По кривым дифференциального термомагнитного анализа установлено присутствие в осадках магнетита. Согласно диаграмме Дэя–Данлопа магнитные зерна образцов озера Банное представляют собой комбинацию однодоменных и многодоменных (псевдооднодоменных) зерен с долей многодоменных от 70 до 92 %. Вариации магнитной восприимчивости и компонент магнитной восприимчивости рассмотрены в связи с климатическими стадиями голоцена по шкале Блитта–Сернандера. ***Выводы.*** Установлено, что вариации магнитных свойств изученных отложений согласуются с климатическими этапами голоцена по шкале Блитта–Сернандера. Вариации магнитных свойств осадков озера Банное корреспондируют с глобальным событием Бонда 8 (~11100 к.л.н), а также отображают региональные события аридизации, которые произошли ~4500 и ~2000 лет назад. Полученные данные дополняют уже существующие климатологические данные и будут интересны широкому кругу исследователей – от палеоклиматологов до лимнологов и экологов.

Ключевые слова: магнитные методы, палеоклимат, озерные осадки, голоцен, условия осадконакопления

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Introduction

Global, regional, and local ecological and geological information is recorded in lacustrine sediments [1]. A comprehensive study of lacustrine sediments can produce the most complete reconstruction of the sedimentation environment. Today, despite the growth in the number and depth of paleoclimatic studies, there is still a lack of data and material indicators (including magnetic and mineralogical indicators) on inland climate changes.

It is known that variations in the magnetic properties of modern lacustrine sediments reflect different environmental factors: inflow into the sedimentation basin; source of the sedimentary material; water level fluctuations; climate, and other sedimentary conditions [2]. Magnetic properties are relatively easy to measure, and this makes them a very convenient tool for detailed recording of variations in sediment properties, revealing changes and trends in sedimentary conditions, and correlation of sedimentary strata. These magnetic properties include magnetic susceptibility (MS) and normal-magnetization coercive spectra [3].

MS values are sensitive to the degree of weathering. During dry periods, erosion and chemical weathering slow down, which leads to a decrease in the magnetic content of the sediment [4]. On the other hand, during humid periods, chemical weathering and erosion intensify, which leads to higher values of MS. Thus, during warm/humid periods, higher MS values can be expected, and vice versa [5]. Curves of magnetization norms determine the characteristics of hysteresis, domain structure, and size of ferrimagnetic grains [6], characterize the role of para-, ferro-, and superparamagnetic components to the induced magnetization and MS [7]. The paramagnetic component reflects the inflow of allothigenic material into the sedimentation basin, which in its turn correlates with the humidity level and the water level. The ferrimagnetic component is often represented by single-domain (SD) biogenic (authigenic) grains [2], as well as by multi-domain (MD) clastic material of an allothigenic nature.

The paramagnetic component has the greatest influence on the MS, because the ferromagnetic content in modern lacustrine sediments is usually small, and most biogenic materials, and water, are diamagnetic [3, 8]. The biogenic contribution to the MS is probably defined by the superparamagnetic component associated with the smallest (~30 nm) grain fraction [3].

Thus, magnetic properties of lacustrine sediments can be used to identify supply sedimentary material variations and hence climate and other environmental changes in the South Urals during the Quaternary [3, 8].

Sediments of less than 10 lakes in the Southern Urals were subjected to magnetic studies; the results of these studies were recorded in [8, 9]. The cyclical alternation of distinctive dry and wet periods, which was noted in the studied sediments, was due to the water availability factor in steppes and forest-steppes of the Southern Urals.

The magnetic properties of sediments in Lake Bannoe were studied for the first time. A review of regional studies on lacustrine sediments shows that magnetic data can develop and complement existing common ideas about lacustrine sedimentary environments.

Materials and methods

The research aim is to study the MS and normal-magnetization coercive spectra of Lake Bannoe (South Urals) sediments in consideration of the Holocene climate stages.

The research objectives included the following:

- study the magnetic properties of the bottom sediments of Lake Bannoe;
- analyze MS variations and their reflection of climatic events and environmental trends;
- establish the characteristics of hysteresis, domain structure, and sizes of ferrimagnetic grains;
- evaluate the role of the contribution of magnetic parameters (k_para-, k_ferro-, and k_super to the total MS) and fluctuations of the biogenic component during periods of aridization and humidification in the South Urals.

Lake Bannoe (53°35'48.13”N 58°37'47.28”E) is located in the Southern Urals (Fig. 1). The altitude of the lake is 434 m, the width is ~1.9 km, the length is ~4.2 km, and the basin area is 36.3 km^2. The lake is of tectonic origin [10].

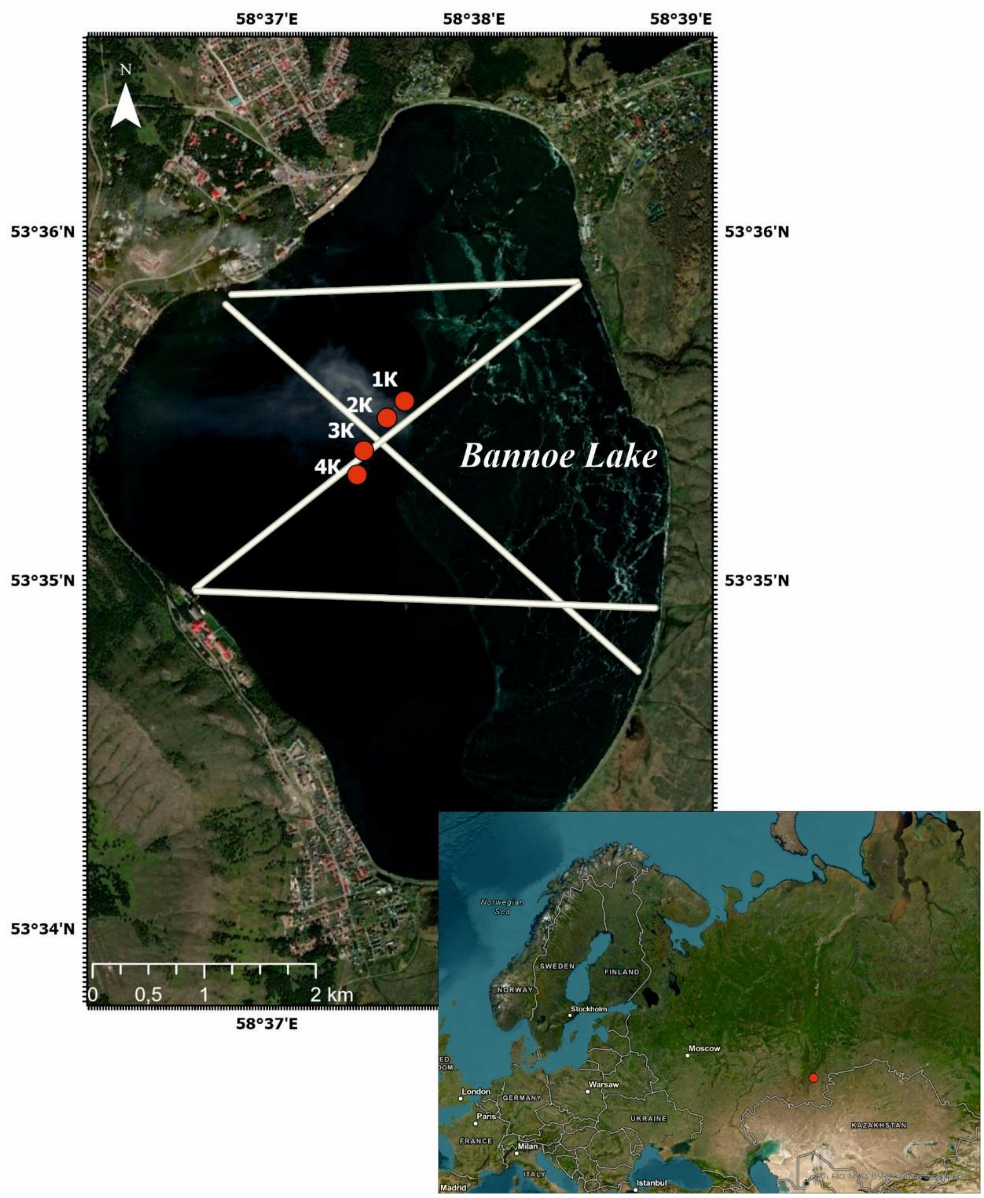


Fig. 1. Location of Lake Bannoe, selected core columns and seismoacoustic profiles

Рис. 1. Расположение озера Банное, отобранных керновых колонок и сейсмоакустических профилей

The drill cores were collected with a hydraulic sampler, described in detail in [11]. The basic principle lies in pressing the core barrel into the sediment with hydraulic force and extraction of quality core samples up to 5.5 meters long. The sampling location was selected based on seismoacoustic data (the area of undisturbed layering).

Four core columns with length from 380 to 512 cm (Fig. 1, Table 1) were selected based on acoustic studies [8, 9, 12]. The total number of taken samples was 954, with a sampling step of 2 cm.

Table 1. *Basic information about the sampling points*

Таблица 1. *Основные сведения точек отбора керна*

Coordinates Координаты	Core length (m) Длина керна (м)	Number of samples (pcs) Количество образцов (шт.)
N 53° 35'30.93” 53° 35'30,93” с.ш. E 58° 37'39.97” 58° 37'39,97” в.д.	3.80	190
N 53° 35'27.87” 53° 35'27,87” с.ш. E 58° 37'34.75” 58° 37'34,75” в.д.	5.08	254
N 53° 35'22.36” 53° 35'22,36” с.ш. E 58° 37'28.22” 58° 37'28,22” в.д.	5.08	254
N 53° 35'18.08” 53° 35'18,08” с.ш. E 58° 37'26.08” 58° 37'26,08” в.д.	5.12	256

The sediment section of Lake Bannoe is represented (from bottom to top) by gray-blue clay with shell fragments (the interval of 508–466 cm, 42 cm thick) and dark green to gray-green silt (the of interval 466–0 cm, 466 cm thick).

The lake age model was constructed based on the radiocarbon dating of 9 samples. According to the model, the lacustrine sediment record in investigated column can be estimated by duration ~12.5 thousand years old [8, 13].

The MS was measured in 954 dried samples of 2–15 g weight at room temperature from all the core columns using MFK-1A Kappabridge (Advanced Geoscience instrument company (AGICO)). The measurements were carried out at a standard frequency of 976 Hz. The obtained values of the MS were normalized by sample weight.

MS values in sediments depend on the weathering process. Drought periods slow down erosion and chemical weathering, which reduces the content of magnetic minerals in the sediment [4]. On the other hand, humid periods are characterized by active chemical weathering and erosion, which results in higher MS values. Therefore, high MS values can be expected during warm/humid periods, and vice versa [5].

The hysteresis parameters of the studied sedimentary deposits were determined using a coercive spectrometer (J_meter) [7, 14]. The J_r channel (residual magnetization) has a sensitivity of $\sim1\cdot10^{-8}$ A·m^2; the J_i channel (inductive magnetization) has a sensitivity of $\sim1\cdot10^{-6}$ A·m^2. The maximum magnetizing field induction is 1.5 mT.

The hysteresis parameters reflect the size of magnetic grains, which depends on physical and chemical conditions in the sedimentary environment [6, 15]. Therefore, the magnetic hysteresis loop can be used to determine the domain state and the approximate size of magnetic particles [16] in order to assess the contribution of paramagnetic minerals to the magnetic behavior of sediments [17].

Coercive spectrometry was used as a primary method to study 510 samples taken from core columns # 3 and # 4. The hysteresis parameters (saturation magnetization (M_s), saturation remanence (M_{rs}), and coercivity (B_c)) were determined from hysteresis curves, whereas the coercivity remanence (B_{cr}) was determined from the magnetic backfield curve. These parameters were used, among others, to infer the magnetic domain state as well as the predominant grain size of ferrimagnetic minerals.

The magnetic hysteresis parameters reflect the size of magnetic particles, the composition of magnetic grains [3, 6, 15] and the contribution of paramagnetic (k_para), ferromagnetic (k_ferro) and superparamagnetic (k_super) components to the MS [3]. Allothigenic material is considered as the primary source of k_para, while the k_ferro and k_super components can be of mixed (allothigenic and/or authigenic) nature [3].

Thermomagnetic analysis is used for diagnosing the composition of the ferrimagnetic fraction in rocks [7, 14, 18]. Induced magnetization based on differential thermomagnetic analysis (DTMA) [18] was performed on an auto-registering magnetic torsion balance using the zero method. Before measurements, the dried sample was grinded and placed in a measuring container – a quartz tube, 3–4 cm long and 3–5 mm in diameter. Each sample was heated twice in a magnetic field of 0.5 mT at a heating rate of 100°C/min. The result was the temperature dependences of the induced magnetization Ji(T) obtained during the first and second heating.

Electron microscopy was carried out at the Interdisciplinary Center for Analytical Microscopy (Kazan Federal University). The morphology and elemental composition of magnetic particles in the

Lake Bannoe sediments were studied using the Carl Zeiss "Merlin" field emission scanning electron microscope equipped with the Aztec X-MAX (for elemental analysis) detector. The resolution was 127 eV.

Results

Fig. 2 presents the MS measurement results. The MS values of core column # 1 vary in the range of $(0.88–3.58)·10^{-7}$ m^3/kg. The MS of core column # 2 vary in the range of $(1.01–4.49)·10^{-7}$ m^3/kg. The MS values for core column # 3 vary from $0.93·10^{-7}$ to $3.63·10^{-7}$ m^3/kg. The MS values of core column # 4 vary from $1.05·10^{-7}$ to $7.87·10^{-7}$ m^3/kg.

High values of magnetic susceptibility were recorded at a depth of 508–480 cm in core sample # 2 and at a depth of 486–512 cm in core sample # 4, which may be due to an increased supply of allothigenic material to the sedimentation basin. DTMA revealed that magnetic minerals at these depths are mainly represented by magnetite, which was confirmed by the results of SEM (Fig. 3, 4).

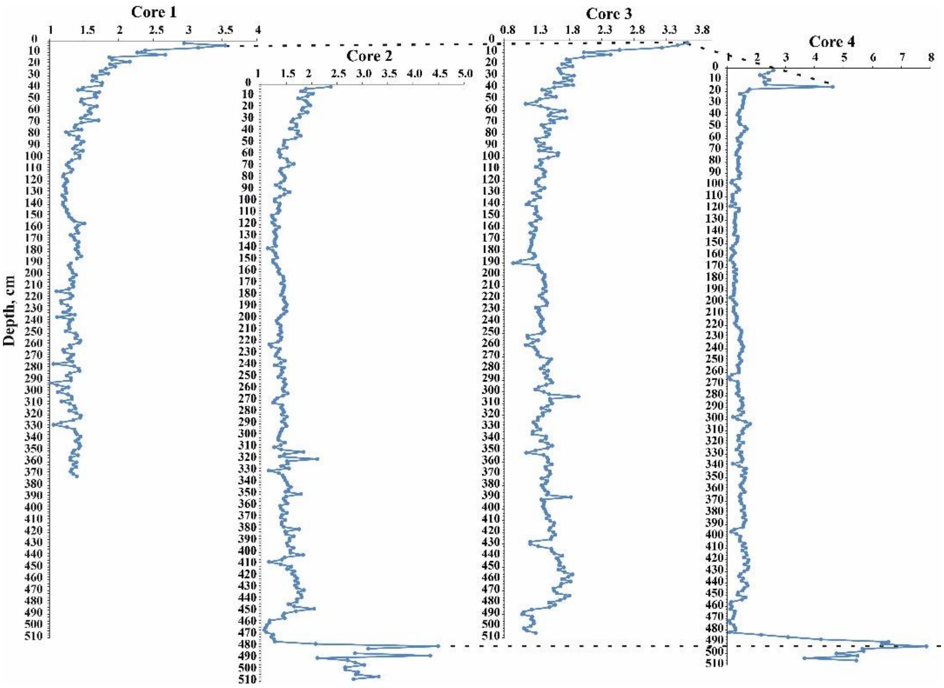


Fig. 2. *Variations of MS ($·10^{-7}$ m^3/kg) with depth*

Рис. 2. *Вариации магнитной восприимчивости озера Банное по глубине ($·10^{-7}$ м³/кг)*

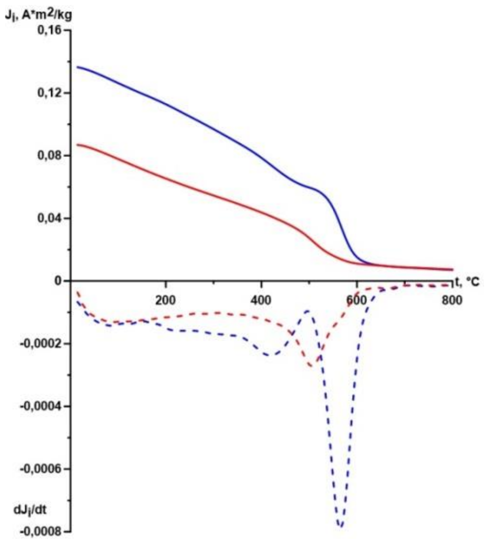
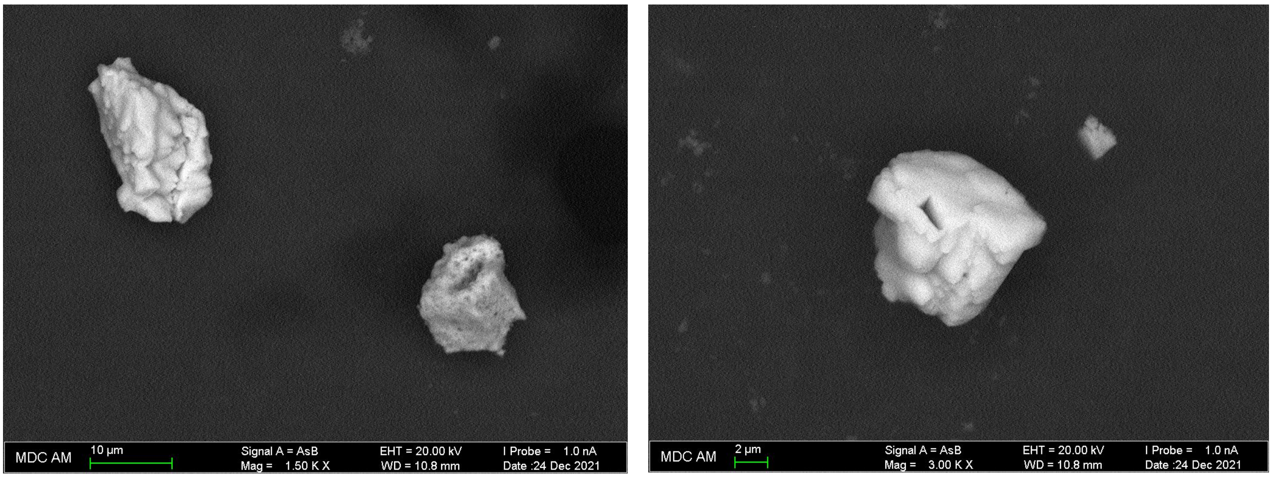


Fig. 3. *DTMA results for core piece # 1053 taken from core sample # 4. Blue line indicates the first heating, red line is for the second heating; solid lines are integral curves, dotted lines are differential curves*

Рис. 3. *Результаты дифференциального термомагнитного анализа образца 1053 керновой колонки № 4. Сплошная синяя линия – первый нагрев, сплошная красная – второй нагрев; пунктирная синяя линия – дифференциал первого нагрева, пунктирная красная – дифференциал второго нагрева*



A B

Fig. 4. *Electron microscopy images of detrital magnetite at a depth of 500 cm in the Lake Bannoe, atom. %: A) Fe – 27.36; O – 54.32; C – 18.09; Al – 0.08; Si – 0.11; Cu – 0.11; B) Fe –42.66; O – 47.15; C – 9.81; Al – 0.14; Si – 0.05; Cu – 0.19*

Рис. 4. *Электронно-микроскопические снимки обломочного магнетита на глубине 500 см озера Банное, атом. %: A) Fe – 27.36; O – 54.32; C – 18.09; Al – 0.08; Si – 0.11; Cu – 0.11; B) Fe –42.66; O – 47.15; C – 9.81; Al – 0.14; Si – 0.05; Cu – 0.19*

The Day–Dunlop plot [6, 15] (Fig. 5) shows the magnetic hysteresis parameters obtained for two core columns (# 3 and 4).

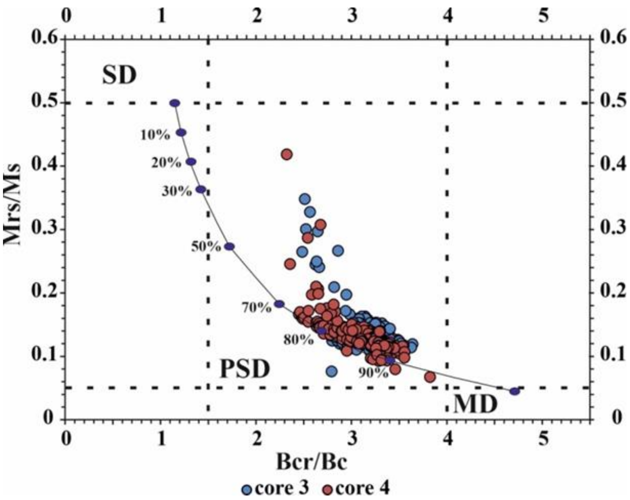


Fig. 5. *Day–Dunlop plot [6, 15]: blue circles refer to core column # 3, red circles refer to core column # 4*

Рис. 5. *Диаграмма Дэя–Данлопа [6, 15] для керновых колонок: синие кружочки – керновая колонка № 3, красные – № 4*

Alternatively, the proximity of the samples to the mixing curve implies that the magnetic grains could be a combination of SD and MD (PSD) grains with a MD proportion between 70 and 92% [15].

The MS components determined for core sample # 3 changes with depth (Fig. 6).

The Younger Dryas is characterized by low values of magnetic susceptibility, which vary from $1.1{\cdot}10^{-7}$ to $1.28{\cdot}10^{-7}$ m^3/kg. The contributions of para-, ferro-, and superparamagnetic components are also relatively low with averages of $6.71{\cdot}10^{-5}$ and $2.03{\cdot}10^{-5}$, and $0.03{\cdot}10^{-5}$, respectively.

The Preboreal is characterized by an increase in the values of magnetic susceptibility (up to $1.8{\cdot}10^{-7}$ m^3/kg). The contributions of para-, ferro- and superparamagnetic components also increase; their average values are $6.64{\cdot}10^{-5}$ and $4.05{\cdot}10^{-5}$, $0.04{\cdot}10^{-5}$, respectively.

In the Boreal, there is again an increase in the MS values (to $1.85{\cdot}10^{-7}$ m^3/kg) and the contribution of para- and ferromagnetic components. In this stage, the maximum values of the paramagnetic and ferromagnetic components reach $8.3{\cdot}10^{-5}$ and $6.75{\cdot}10^{-5}$, respectively.

The Atlantic stage corresponds to an increase in the MS values up to $1.94{\cdot}10^{-7}$ m^3/kg. At this stage, the maximum value of the paramagnetic component is also recorded $9.18{\cdot}10^{-5}$). An increase in the values of magnetic susceptibility and the paramagnetic component may indicate increased input of allothigenic material into the lake. The superparamagnetic component also becomes more explicit, and its value ranges between $0.03{\cdot}10^{-5}$ and $0.06{\cdot}10^{-5}$.

With the beginning of the Subboreal, a decrease in the values of magnetic parameters is observed: magnetic susceptibility varies from $0.93{\cdot}10^{-7}$ to $1.63{\cdot}10^{-7}$ m^3/kg, the paramagnetic component varies from 5.05 to $7.4{\cdot}10^{-5}$. The superparamagnetic component ranges between 0.02 and $0.07{\cdot}10^{-5}$. The decrease in the values of magnetic parameters characterizes the climate change during this stage. The ferromagnetic component at the end of the Subboreal increases to the maximum of $7.88{\cdot}10^{-5}$.

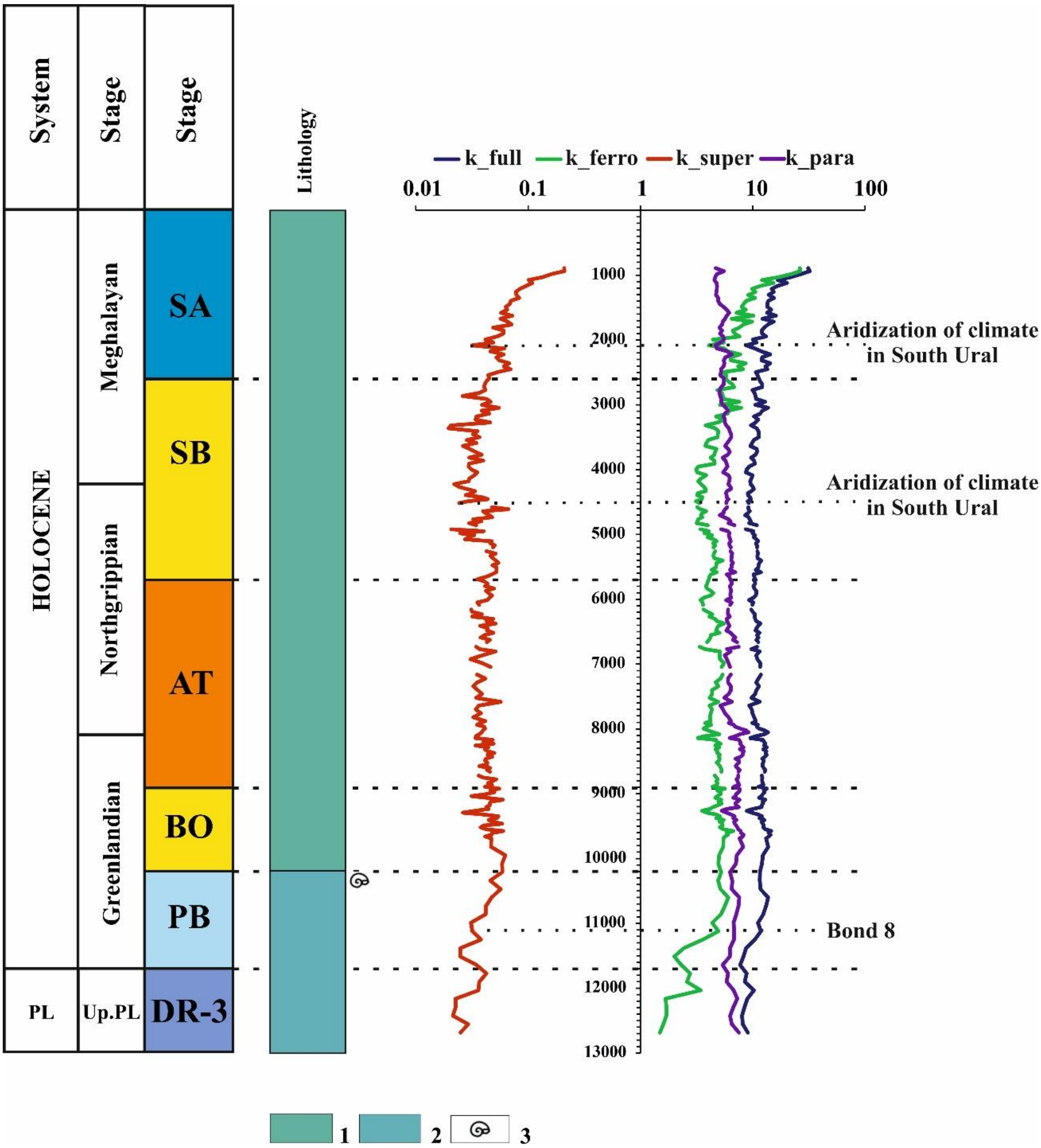


Fig. 6. *Variations of magnetic parameters obtained for core sample # 3 in context of the Blytt–Sernander classification [19–22]. Legend: 1 – dark green silt; 2 – gray-blue clay; 3 – shells*

Рис. 6. *Вариации магнитных параметров образцов керновой колонки № 3 в связи с климатической стадийностью Блитта–Сернандера [19–22]. Условные обозначения: 1 – темно-зеленый ил; 2 – серо-голубая глина; 3 – раковинный детрит*

The Subatlantic is characterized by an increase in the MS values (to $3.63 \cdot 10^{-7}$ m^3/kg), the ferromagnetic component (to $9.47 \cdot 10^{-5}$) and the superparamagnetic component (to $0.21 \cdot 10^{-5}$). The values of the paramagnetic component, on the other hand, decrease (with average of $6.49 \cdot 10^{-5}$), which indicates a decrease in the supply of paramagnetic minerals (silicates) to the lake. An increase in the values of MS and the ferromagnetic component can be associated with either an increased input of allothigenic material, the contribution of lake biota or anthropogenic pollution [3].

Discussion

The variations in MS, k_para and k_ferro components were analyzed in context of the Blytt–Sernander classification [20–22] (Fig. 4). The Blytt–Sernander classification is a series of north European climatic periods or phases based on the study of Danish peat bogs by Axel Blytt and Rutger Sernander.

Magnetic susceptibility and its components vividly respond to any changes in the supply of allothigenic material, which in turn is sensitive to changes in humidity [2, 9].

Low values of MS are characteristic of the Younger Dryas. The contributions of k_para, k_ferro and k_super components are also relatively small. Low values such as these can indicate cold and dry climate.

The Preboreal is known for significant climate warming and rise in the world sea level [23]. This stage is also characterized by increased MS, k_para, k_ferro, and k_super components. An increase in the values indicates a transition from cold and dry climate of the Late Pleistocene to warm and humid conditions of the Holocene [4]. The Bond global event [24] synchronized with an increase in k_ferro values (Fig. 4) due to allothigenic and authigenic sedimentary material filling the newly formed lake basin.

During the Boreal, an increase in MS and the contributions of k_para and k_ferro components can be observed. An increase in MS and k_para, k_ferro and k_super components implies an increased inflow of allothigenic material into the sedimentation basin. The study of sedimentary deposits in Lake Syrytkul (South Ural, Russia) [25] showed that the climate in the South Urals was warm and dry ~10300–~9000 years ago.

The Atlantic is characterized by increased MS and k_para component. This may indicate an increased inflow of allothigenic material into the lake basin [4]. Therefore, we can assume that the climate continued to reflect warm-and-humid trend. This trend is confirmed by data on Lake Ufimskoe (South Ural, Russia) obtained for the interval of time between ~9000 and ~5800 years ago [26]. The local drop of MS which occurred ~8000 years ago reflects a decrease in climate humidity recorded as a significant increase in the organic content in sediments of Lake Turgoyak (South Ural, Russia) [27].

At the beginning of the Subboreal, a decrease in the magnetic parameters (MS and k_para component) indicates the climate change, namely, a decrease in humidity. Aridization in the Subboreal (~4,500 years ago) is confirmed by diatom analysis data from Lake Ufimskoe [26].

The Subatlantic is characterized by an increase in MS and the k_ferro component. The k_para component, on the other hand, decreases, which indicates a decrease in the paramagnetic mineral (silicate) inflow to the lake. An increase in the values of MS, the k_ferro, and k_super can be associated with either an increased input of allothigenic material or the contribution of lake biota [4]. Decreased input of allothigenic material is explained by aridization, which took place ~ 2000 years ago. This is consistent with regional data on Lake Syrytkul and Lake Talkas (South Ural, Russia) [27, 28].

Conclusion

The magnetic properties of sediments in Lake Bannoe were studied for the first time. The analysis of the MS variations showed that they reflect climate events and environmental trends. The hysteresis parameters, the domain structure and ferrimagnetic grain sizes were obtained using the curves of normal-magnetization.

Also the contribution of magnetic parameters such us k_para-, k_ferro-, and k_super components to the total MS were obtained.

The inflow of allothigenic clastic material into the sedimentation basin is reflected in variations of the paramagnetic and superparamagnetic content. The k_ferro component is represented by SD grains (presumably of authigenic origin) and MD clastic grains. Variations in the biogenic component correlate with the total bioproductivity of the lake and variations in the summer paleotemperature. The periods of aridization and humidization in the South Urals identified during the study are compared with the Blytt–Sernander classification. Variations in magnetic properties of sediments in Lake Bannoe reflect the Bond event #8 (~11100 years ago) and regional aridization events which occurred ~4500 years ago and ~2000 years ago.

The results obtained during this study complement already existing paleoclimatology data, which will be interesting to a wide range of researchers - from paleoclimatologists to limnologists and ecologists.

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