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On the Possibility of Constructing a Quantitative Paleoreconstruction of the Altai Mountains Climate Based on Scanning SR-XRF Data on the Bottom Sediments of Lower Multa

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Abstract—Bottom sediments in mountain lakes archive regional and global environmental changes, including those related to climate change. For fresh highland lakes of the Altai region, the main sources of bottom-sediment material are terrigenous demolition and organics of allochthonous and autochthonous origin. Changes in air temperature and amount of atmospheric precipitation modulate the elemental composition of bottom sediments determined by the ratio of incoming terrigenous and organic material. Analysis of variations in the elemental composition by the core depth of bottom sediments can provide information on changes in the region's main climatic parameters over past millennia with high detail determined by the spatial (sequential—temporal) resolution of the analytical method. The method of scanning synchrotron-radiation-induced X-ray fluorescence analysis (SR-XRF) is used for climatic reconstruction of high time resolution, which allows one to obtain a continuous series of elemental composition according to core depth with required spatial resolution. The article presents the results of studying a core of bottom sediments from Multa Lakes (Altai) using analytical microstratigraphy techniques, including scanning SR-XRF. A transfer function was constructed that relates the chemical composition of dated core intervals for the 1940–2015 time period with regional instrumental meteorological observations. The possibility of creating quantitative climate reconstructions based on data from scanning SR-XRF is shown.

Keywords: synchrotron radiation, X-ray fluorescence analysis, microscanning, lake (lacustrine) bottom sediments, the Altai Mountains, climate reconstructions

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INTRODUCTION

Researchers consider the global positive trend of average annual temperatures of recent decades as the cumulative result of the manifestation of existing climatic cyclicity and anthropogenic impact on the natural environment [1]. The identification of a relationship between natural and anthropogenic components in the process of global warming is one of the issues for discussion important for building correct forecast models of climate dynamics. Of great importance in resolving this issue is the development of methodological approaches that make it possible to construct quantitative climatic paleoreconstructions that are sufficiently long in time, in the analysis of which important information can be obtained about the natural patterns of the climate-formation process.

One of the most important sources of data used for paleoclimatic reconstructions are the bottom sediments of lakes, the study of which using a set of high-resolution methods makes it possible to identify both local and regional natural and climatic changes [2]. The formation of bottom sediments in freshwater lakes depends on external conditions that determine the supply of sedimentary material from the catchment area. At the same time, stratified bottom sediments contain information about the geological structure of the catchment area and the dynamics of sediment supply due to the accumulation of certain chemical elements [3].

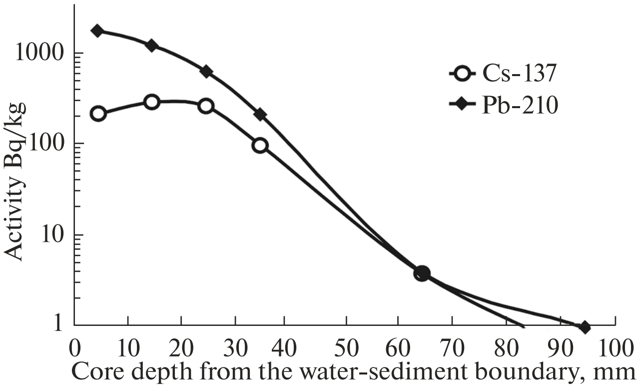

Fig. 1. Activity profiles of Cs-137 and Pb-210 along the depth of core MN-02.

For fresh lakes of the Altai region, the main sources of bottom-sediment material are terrigenous-demolition products and organic material of allochthonous and autochthonous origin. Changes in the temperature of near-surface air and the amount of atmospheric precipitation largely determine the structure and elemental composition of bottom sediments determined by the ratio of incoming terrigenous and organic material. By studying a cross section of modern bottom sediments and comparing the chemical composition and structure of the cross section's dated intervals with external weather and climatic factors, it is possible to obtain detailed information on the process of sedimentation with the identification of stable links between sediment indicators and environmental parameters, primarily with regional instrumental meteorological data and hydrological observations [4].

Analytical microstratigraphy of Late Holocene sediments of lakes using the scanning X-ray fluorescence analysis (XRF) method with synchrotron-radiation beams (SR-XRF) makes it possible to obtain information for constructing regional climatic paleoreconstructions with an annual time resolution, which are comparable in quality to the data of instrumental meteorological observations [5]. The comparison of analytical data on the elemental composition of the dated layers of bottom sediments and instrumental meteorological observations on the timeline makes it possible to identify geochemical climate indicators and construct transfer functions for calculating paleoreconstructions.

EXPERIMENTAL

The natural monument (specially protected natural area, SPNA) Multa Lakes is located at the northwestern end of the Katun ridge, in the upper part of the valley of the Multa River (right tributary of the Katun River, Gorny Altai). Lower Multa is located at an altitude of 1627 m. The lake's length is 2370 m and its width is 990 m.

The core sampling of bottom sediments was carried out in 2020 from the deepest point of the lake (22 m) using an Uwitec gravity corer. The core-top integrity was monitored during core sampling and transportation to Novosibirsk.

The core was opened in laboratory conditions and divided along the sampling axis into two halves. After photographing and description, discrete samples were prepared from one half of the core by cutting with a pitch of 10 mm for various geological and analytical studies. Solid samples impregnated with epoxy resin were prepared from the second half of the core for continuous X-ray fluorescence analysis (XRF) scanning according to the procedure in [5].

ANALYTICAL STUDIES

Isotope Studies

The activity of the distribution of Cs-137 and Pb-210 isotopes over the depth of the upper core interval (0–100 mm) was obtained using semiconductor low-background gamma spectrometry on a coaxial Ge detector with a low-background cryostat according to the standard method (analyst M. S. Melgunov). The results are presented in Fig. 1.

Scanning SR-XRF of Solid Samples of Bottom-Core Sediments MN02

Scanning SR-XRF was carried out at the Siberian Synchrotron and Terahertz Radiation Centre, Budker Institute of Nuclear Physics at the experimental station "Elemental Analysis" according to a certified technique [6]. XRF scanning was carried out using a monochromatic energy of 23 keV, and the dimensions of the collimated beam on the sample were 1 mm vertically by 10 mm horizontally. The sample moved vertically with a 1-mm step. The measurement time at each point was 20 seconds; the content of more than 20 rock-forming and trace elements and the X-ray density of the sample were simultaneously determined.

RESULTS AND DISCUSSIONS

Geochemical-Data Time Series

The upper-core interval (100 mm from the water–sediment boundary) was tied to the time scale to build an age model for the entire core length based on the distribution of Cs-137 and Pb-210 isotope activity (Fig. 1). The maximum of Cs-137 activity is recorded in the range of 15–25 mm from the water–sediment boundary, which corresponds to the global fallout of 1961–1962. Assuming that the top of the core was taken without loss and damage, the time count started from the year of sampling. According to calculation results, the linear sedimentation rate based on Cs-137 activity lies in the range of 0.26–0.44 mm/year (aver-

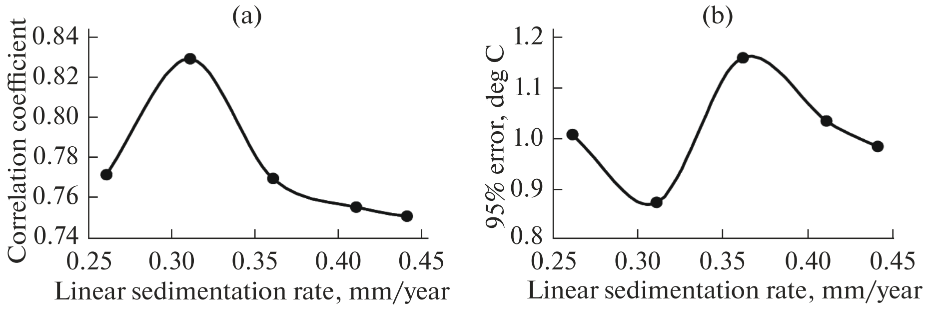

Fig. 2. Change in the correlation coefficient between instrumental temperature observations and their reconstructions by transfer functions (a) and the 95% confidence interval (b) at different deposition rates.

age 0.35 mm/year). The rate estimate for the change in Pb-210 activity was 0.45 mm/year [7]. Thus, the rate of modern sedimentation in Lower Multa lies in the range of 0.26–0.45 mm/year.

The resulting rate estimates have a fairly large spread. To refine the age model, five time series of geochemical data were constructed with fixed linear sedimentation rates within the above interval (0.26, 0.31, 0.36, 0.41, and 0.44 mm/year). In the X-ray fluorescence analysis (XRF) of core samples, the scanning step was 1 mm vertically; therefore, the scanning result at different deposition rates is an average characteristic of the chemical composition of bottom sediment accumulated over different periods of time: at a rate of 0.26 mm/year for ~four years, at 0.31 and 0.36 for ~ three years, at 0.41 and 0.44 for ~ two years. The time series of geochemical characteristics obtained with this in mind were used for comparison with regional meteorological data in order to identify the most optimal option.

Transfer-Function Construction

As the initial material for calibrating the geochemical-time series based on near-surface air temperature, continuous instrumental observations since 1940 at the Ust'-Koksa weather station, located 33 km northwest of the study object, were used [8].

To construct transfer functions from the entire analytical data set, the following set of parameters was selected: the contents of Br, Zn, Ti, Ga, Rb, Y, Nb, and Th, the Rb/Sr ratio, and the X-ray density of the sample as the ratio of elastic/inelastic scattered radiation (Coh/Inc). On the one hand, this is a set of the most analytically reliable data remaining after rejection according to the criterion: the statistical significance of the analytical signal (the element peak/background ratio in the original spectrogram). On the other hand, the general understanding of the bottom-sediment accumulation process suggests that the Br content reflects the contribution of the organic component and has a positive relationship with the regional temperature, the Y and Nb contents reflect the intensity of terrigenous-material input, and the Rb/Sr ratio characterizes the particle size in the forming sediment. That is, the selected set of characteristic parameters also has meaningful content.

Previously, to bring it to a comparable form, all five different-time versions of the initial geochemical data were reduced to three-year average values using interpolation procedures, i.e., each year on the time scale corresponds to the averaged geochemical characteristic of the core interval accumulated over the previous three years. Then, using the methodological techniques described in detail in [9], the multiple regression method was used to construct functions reflecting the relationship between the geochemical composition of the bottom sediment with the three-year average instrumentally measured regional temperature.

Thus, five transfer equations were obtained for different deposition rates. The selection of the optimal one was carried out according to the following criteria: the maximum correlation coefficient of the initial instrumental temperatures and their reconstruction according to the corresponding transfer function with a minimum 95% confidence interval (Fig. 2).

Calculations made it possible to select the optimal sedimentation rate (0.31 mm/year), at which the connection between the elemental composition of bottom sediments and the regional temperature mode is most clearly manifested. The transfer function for this option has the form:

$$\begin{aligned}\text{Temperature} &= 3.87\text{Br} - 0.75\text{Y} - 0.16\text{Nb} \\ &+ 0.53\text{Th} - 0.76\,\text{Rb}/\text{Sr} - 1.93.\end{aligned} \tag{1}$$

Function (1) is an analytical expression of the empirical dependence of the elemental composition of the dated interval of the bottom sediment on the external temperature during the period of its formation and allows with sufficiently high accuracy and reliability ($r = 0.83$; $n = 76$; 95% confidence interval ±0.87°C) to reconstruct the average three-year near-surface air temperature in the calibration interval 2015–1940 (Fig. 3).

The age model based on data on the distribution of Cs-137 and Pb-210 isotopes over the core interval of

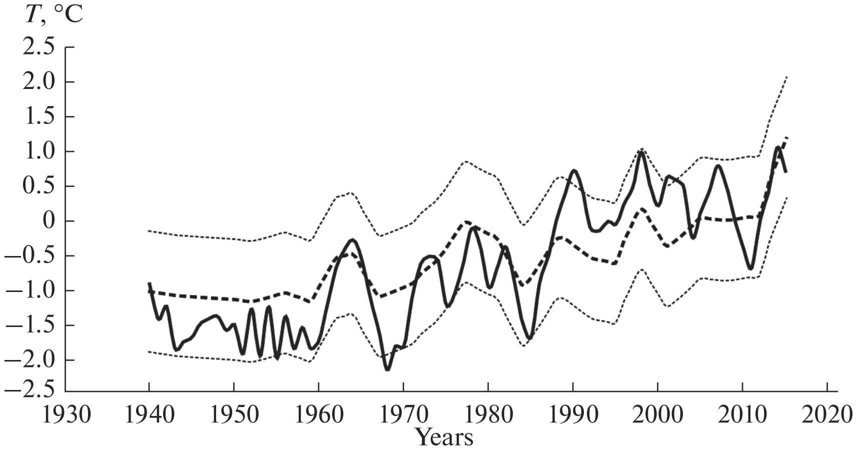

Fig. 3. Average three-year temperature according to instrumental data from the Ust'-Koksa weather station (solid thick line) and its reconstruction according to the chemical composition of bottom sediments (dotted thick line) with an indication of the 95% confidence interval (thin dotted lines).

0–100 mm does not allow the dating of deeper layers. Therefore, a temperature reconstruction was built only for the last 350 years (108 mm of core from the water–sediment boundary), based on the assumption of maintaining the average deposition rate in this time interval.

The resulting temperature chronology was compared with the reconstruction of average annual temperatures for Russian Altai, constructed using dendroclimatic data [10] (Fig. 4).

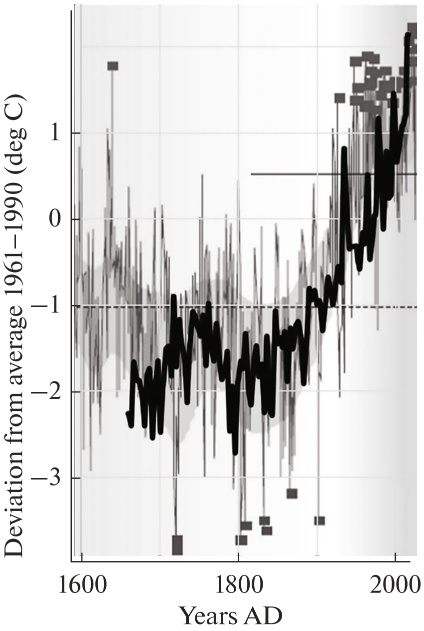

Fig. 4. Reconstruction of the average three-year temperatures of the Altai region, built on the basis of the SR-XRF scanning of cores of bottom sediments of Lower Multa over the past 350 years (black line) in comparison with a temperature reconstruction according to dendrological data (gray line) built for the Russian Altai [10].

Comparative analysis shows a good agreement between the main temperature trends and the absolute values of these reconstructions based on different proxies (biological and geochemical).

CONCLUSIONS

The use of analytical microstratigraphy data (scanning SR-XRF) of sedimentary sections of mountain lakes makes it possible to obtain a large set of information on the composition of lake bottom sediments, tied to the timeline. High temporal resolution in the analysis of geochemical data makes it possible to compare instrumental regional meteorological observations and information on the composition of bottom sediments. This approach makes it possible to identify geochemical indicators that reflect the stable response of the composition of bottom sediments to changes in regional meteorological parameters. The constructed transfer functions can be successfully used to construct quantitative climate reconstructions of high temporal resolution for lake cross sections containing stratified sediments that have not undergone significant post-sedimentary changes.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. *IPCC, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers* (Cambridge Univ. Press, Cambridge, 2021). https://www.ipcc.ch/report/ar6/wg1/.
2. D. D. Kuznetsov and D. A. Subetto, *Stratigraphy of Bottom Sediments of Lakes of the Karelian Isthmus* (GEOS, Moscow, 2019) [in Russian].
3. V. A. Dauval'ter, *Geoecology of Bottom Sediments*(Murm. Gos. Tekh. Univ., Murmansk, 2012) [in Russian].
4. A. V. Dar'in, E. L. Gol'dberg, I. A. Kalugin, M. A. Fedorin, K. V. Zolotarev, and N. V. Maksimova, Poverkhn.: Rentgenovskie, Sinkhrotronnye Neitr. Issled., No. 12, 53 (2003).
5. A. V. Dar'in, I. A. Kalugin, and Ya. V. Rakshun, Bull. Russ. Acad. Sci.: Phys. **77**, 185 (2013). https://doi.org/10.3103/S1062873813020111
6. A. V. Dar'in and Ya. V. Rakshun, Nauchn, Vestn. Novosib. Gos. Tekh. Univ. **51** (2), 112 (2013).
7. P. Appleby, Stud. Environ. Sci. **68**, 441 (1997). https://doi.org/10.106/S0166-1116(09)70124-4
8. Federal Service for Hydrometeorology and Environmental Monitoring. http://www.meteo.ru/climte/temp.php.
9. V. V. Babich, N. A. Rudaya, I. A. Kalugin, and A. V. Dar'in, Sib. Ekol. Zh. **22**, 497 (2015). https://doi.org/10.15372/SEJ20150401
10. U. Buntgen, V. S. Myglan, F. C. Ljungqvist, M. McCormick, N. Di Cosmo, M. Sigl, and A. V. Kirdyanov, Nat. Geosci. **9**, 231 (2016). https://doi.org/10.1038/ngeo2652

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