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Dolichospermum lemmermannii (Nostocales) bloom in world's deepest Lake Baikal (East Siberia): abundance, toxicity and factors influencing growth

Bondarenko N.A.[1], Tomberg I.V.[1], Shirokaya A.A.[1]*, Belykh O.I.[1], Tikhonova I.V.[1], Fedorova G.A.[1,2], Netsvetaeva O.G.[1], Eletskaya E.V.[1], Timoshkin O.A.[1]

[1] *Limnological Institute, Siberian Branch of the Russian Academy of Sciences, Ulan-Batorskaya Str., 3, Irkutsk, 664033, Russia*
[2] *Russian State University of Justice, Ivana Franko Str., 23a, Irkutsk, 664074, Russia*

ABSTRACT. Mass development of the cyanobacteria *Dolichospermum* (*D. lemmermannii* as the dominant species) was reported in the coastal zone of Bol'shye Koty Bay (western coast of the southern basin), towards the end of July to the beginning of August in 2019. Blooms were observed as 1–1.5-m wide bands adjoining the shoreline and stretched uninterrupted over 2 km. Abundance of cyanobacteria in blooms varied within 7.2–71.9 thousand cell mL^{-1}, with 0.73–7.20 g m^{-3} biomass attained. Maximal concentration was observed opposite the biological station of Irkutsk State University, a frequently visited place that was hosting participants of several conferences at that time. Hydrochemical analysis of samples collected four days after continuous heavy rains showed much higher concentrations of nutrients in contrast with the data obtained a week before (24 July), which is normal for that season. Nutrient concentrations were elevated relative to long term averages by 3 to 30 fold: with phosphate concentrations up to 0.200 mg L^{-1}, ammonium ions 0.29 mg L^{-1}, and nitrates 0.31 mg L^{-1}. Possible reasons for the harmful freshwater cyanobacterial bloom that is unusual for this part of the lake are discussed. Excessive proliferation of common cyanobacteria *D. lemmermannii* in the open lake areas was affected by several factors: long-lasting heavy rains, zero wind, high air (from 13–15°C at night to 29°C in daytime) and water temperatures (from 15°C to 19.2°C); and absence of isolated septic tanks in the nearshore zone.

Keywords: harmful freshwater cyanobacterial bloom, *Dolichospermum lemmermannii*, cyanobacterial ecology, environmental factors, saxitoxin, biotic changes, Lake Baikal

1. Introduction

Cyanobacteria (Cyanophyta, blue-green algae, Cyanoprokaryota) are attributed to prokaryotes, which are organisms with no true nucleus but with oxygenic photosynthesis (Andreyuk et al., 1990; Ecology of cyanobacteria…, 2012). The Cyanobacteria includes over 3,000 ancient unicellular or colonial species inhabiting various environments: fresh and salt waters, soils, barren deserts, hot springs and the Arctic glaciers (Komárek and Anagnostidis, 1998; Briand et al., 2002; Belyakova et al., 2006; Bondarenko and Shchur, 2007; Ecology of cyanobacteria…, 2012; Salmaso et al., 2015).

Cyanobacteria are highly adaptive organisms that proliferate in large amounts, causing water blooms (Paerl et al., 2001; Belyakova et al., 2006; Bondarenko and Shchur, 2007; Sitoki et al., 2012; Ho and Michalak, 2015; Korneva, 2015; Salmaso et al., 2015; Kurashov et al., 2018). Cyanobacterial blooms deteriorate water quality, thus threatening water supplies, decreasing in fish production and impacting recreational use. Most of the Cyanobacteria are considered potentially toxic, endangering both human and animal health (Sirenko and Gavrilenko, 1978; Briand et al., 2002; Belyakova et al., 2006; Sitoki et al., 2012; Belykh et al., 2015a; 2015b; 2016; Ho and Michalak, 2015; Salmaso et al., 2015). In the last few decades, cyanobacteria have received increasing attention from researchers, especially in regard to their toxin production. Several types of cyanotoxins, among which microcystins were the most common, have been identified. These toxins are produced by *Microcystis*, *Anabaena* (presently *Dolichospermum*), *Planktothrix* and *Oscillatoria* genera. Neurotropic saxitoxins (STX) and their analogies called paralytic shellfish toxins (PST) are regarded as the most poisonous (Chorus and Bartram, 1999). In seas, PST are synthesised by dinoflagellates, while in freshwaters by cyanobacteria.

Long-term investigations of Baikal plankton

*Corresponding author.
E-mail address: shirokaya@bk.ru (A.A. Shirokaya)

have found cyanobacteria among the summer plankton (Meyer, 1930; Kozhova, 1959; Popovskaya, 1991). Common colonial Baikal forms include species of *Gloeotrichia* and one of the most species-rich genera *Anabaena* (13 species and their variations). In the middle of the last century, Kozhova (1959) wrote that blue-green algae inhabit only shallow areas of Baikal, including the southern part of Maloe More Strait, nearshore areas of Chivyrkuy and Barguzin bays, Selenga shallows, North Baikal Sor and other small, shallow, well-warmed bays, where one litre of water contains several dozens of algal colonies. For example, the high concentrations of blue-green algae were reported in Bol'shye Koty Bay after strong winds from Selenga shallows during the warming period for the lake (Kozhova, 1959). According to Popovskaya (1991), during summer months, algal blooms occured only in the nearshore zone of Middle and Northern Baikal where the surface water temperature was the highest (up to 12–15˚C) and most occurrences of windless days. Hence, in such days, the abundance of *Anabaena* and *Gloeotrichia* genera reached 30 thousand cell mL^{-1} and biomass 3 to 6 g m^{-3}. In the 1980s, *Anabaena* species showed rapid growth in their biomass (Popovskaya, 1991). Blooms visible to the naked eye also covered large areas in the pelagic zone of the middle and northern lake basins from July to August. However, this phenomenon did not last long and was evidently caused by intensive proliferation of different species of *Anabaena*; most of all *A. lemmermannii* (Bondarenko, 2009).

Recently, various constituents of the Baikal nearshore algal community have undergone changes (Kravtsova et al., 2014; Timoshkin et al., 2016). Long-term studies (Kozhova, 1959; Antipova, 1974; Votintsev et al., 1975; Izmest'eva, 1988; Popovskaya, 1991; Bondarenko et al., 2012; Bondarenko and Logacheva, 2017) revealed significant restructuring of the lake's phytoplankton community, including the littoral zone. So far none of the publications reported mass blooms of *Anabaena* (currently termed *Dolichospermum*) under dominance of *A. lemmermannii* in the nearshore area of Bol'shye Koty Bay, although small numbers of the algae occurred early and now in the pelagic zone of this area and, in some years, its abundance was as many as 10 cells mL^{-1} (Antipova, 1974).

In late July to early August 2019, high concentrations of planktonic organisms, resembling mass proliferation of cyanobacteria on their colour and visual features, were observed in some locations of Bol'shye Koty Bay. Here we present our findings as indicators of ecological changes in Lake Baikal with special attention to the possible impact in the nutrient loading.

2. Materials and methods

2.1. Study sites and sampling

Bol'shye Koty Bay (51˚54'10.44''N, 105˚04'14.06''E) stretches along the western side of the southern basin of Lake Baikal (Fig. 1). There is a settlement by the same name on the shore with a Biological station of Irkutsk State University (ISU hereafter), and another station of a Research Institute of Biology (ISU). Both stations provide facilities to the university students and the staff of the Biology Institute participating in summer practice and field work. Approximately 1 km south of the Biological station is a field station of the Limnological Institute SB RAS (LIN hereafter). The University Biological station regularly organises international workshops, scientific conferences and meetings in summer. In July 2019, the station was frequently visited: it welcomed the 19th International Baikal Summer School on Physics of Elementary Particles and Astrophysics, Russian-American Summer School on Biology and a refresher course in teaching Russian as a foreign language (not less than two hundred visitors in total). In the summer, the small settlement also attracts many tourists.

To delineate the bloom-affected areas and determine the dominant organisms, we made visual observations of the nearshore zone within the limits of the bay (Fig. 1), starting from the field station of LIN (the southernmost point, site No. 2) to hotel Mayak (the northernmost point, site No. 3). The total length of the zone studied was 2.5–3 km. Samples for organism identification were directly collected from the blooms at the water's edge, and conditionally non-bloom locations were chosen as reference sites (site No. 3).

Microphotographs of the microorganisms dominating the samples were taken using a Meiji Techno Co. microscope with x40, x100 and x400 magnification by an attached ToupView 3.7 (ToupTek) digital camera.

Water for chemical analysis was sampled twice at two sites on the 24th and 31st of July, covering the distance of nearly 2.5–3 km along the shoreline (Fig. 1): opposite the ISU (sampling point No. 1) and the LIN (sampling point No. 2) field stations. Site No. 3 was located north of the first two points at the end of the settlement (Fig. 1).

Sampling of rainfall was carried out using an automatic rain collector "US-320" (Japan), funnel diameter 357 mm in accordance with the manual (Technical manual..., 2000).

The taxonomic composition and plankton abundance were recorded after sampling at all these sites on the 31st of July at the moment of the cyanobacterial bloom.

The air and water temperature dynamics in this area in June–July 2019 were registered by Optic StowAway Temp (C) ONSET Tid Bit Loggers and HOBO Loggers. The measuring frequency was 1 in 30 minutes and they were installed near the lakeshore opposite the field station of LIN. The surface water temperature was measured on the 31st of July, using Checktemp ˚C thermometer.

2.2. Water chemistry analyses

Chemical analyses were performed using conventional freshwater water chemistry methods (Wetzel and Likens, 2000; Khodzher et al., 2017) and

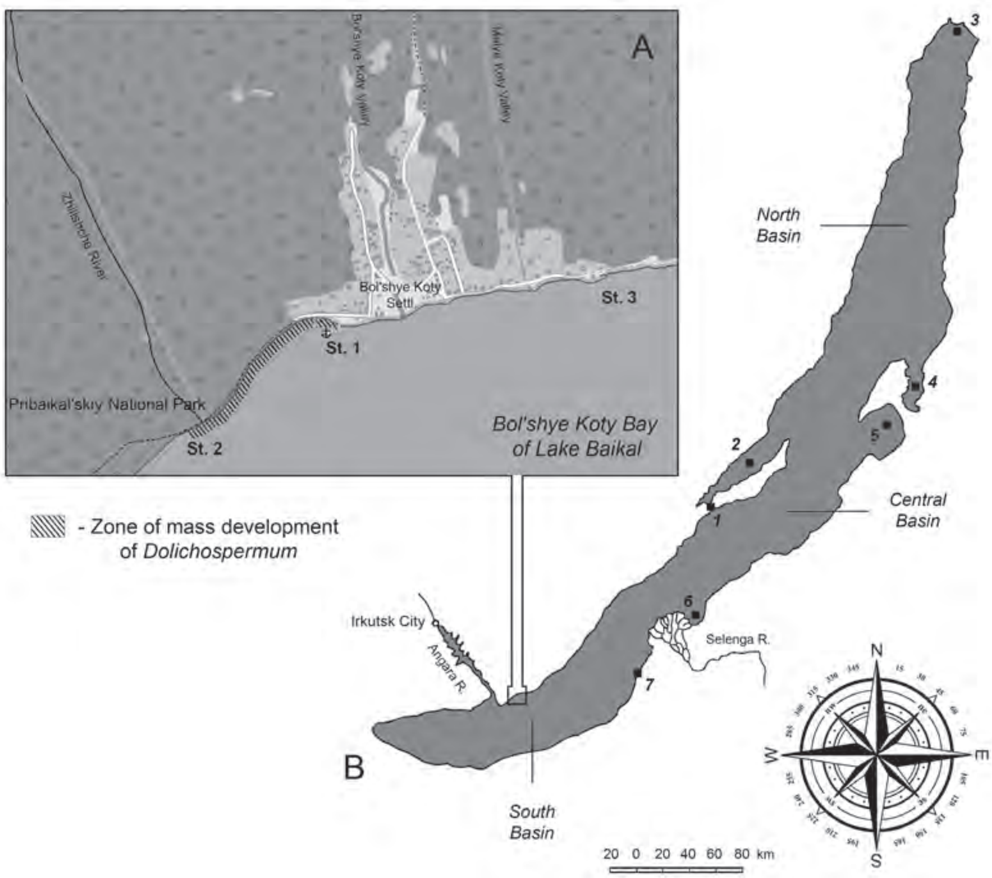

Fig.1. **A.** Schematic map of Bol'shye Koty Bay (Lake Baikal), showing the sampling points (Stations 1–3). **B.** Other locations where cyanobacterial blooms have been observed (1—Malye Ol'khonskiye Vorota Strait, 2—Maloe More Strait, 3—North Baikal Sor, 4—Chivyrkuy Bay, 5—Barguzin Bay, 6—Proval Bay, 7—Istok Sor).

carried out at the Laboratory of Hydrochemistry and Atmosphere Chemistry (LIN) using the equipment of the Shared Research Facilities for Physical and Chemical Ultramicroanalysis LIN SB RAS. The samples were filtered through a cellulose acetate membrane filter, with a pore diameter of 0.45 μm, and the nutrient content in the filtered water was measured using the following colorimetric methods: indophenol blue method for NH_4^+, Griss's method for NO_2^-, Deniges's method for PO_4^{3-} and the nitrate was measured with sodium salicylate (Khodzher et al., 2017).

2.3. Plankton identification

For plankton identification, we fixed 1 L of water with Lugol's solution and then concentrated it by settling. Plankton organisms were counted twice in a 0.1 mL Nageotte chamber under a Peraval light microscope with x720 magnification. The biomass was calculated from the organism number using individual cell volumes (Kiselev, 1956). To determine the biovolume, 100 cells of the species were measured. Cyanobacteria were identified according to Komárek and Anagnostidis (1998).

2.4. Saxitoxins

The presence of STX was recognised by ELISA, using the Abraxis Saxitoxin ELISA kit Abraxis LLC, USA) in according to the manufacturer's protocol. Enzyme-linked immunosorbent assay was carried out by the Stylab Company (Moscow, Russia). The water samples 1 mL in volume and plankton samples (cyanobacteria surface scum) were dried by a vacuum centrifuge at 60°C. Then the plankton dried samples were weighed. The ELISA data were processed by RIDA® SOFT Win.

The genetic and ELISA analyses were carried out after sampling surface water on the 31st of July 2019 and on the 5th of August 2019 during the summer stratification.

3. Results

3.1. Air and water temperature

The air got warmed up to mean diurnal temperatures of 20°C and higher in the study area in July over the last decade (and during 10 days before the bloom), rising to 25–29°C in daytime and never below 13°C at night (13 to 15°C). Late July is the time of intense warming of the water and results in diurnal temperature fluctuations in the Baikal nearshore zone. In this period, even the bottom water temperature at the depth of 3m varied within the range of 15 to 19.2°C (except two cases, the 30th of July and the 1st of August, when morning temperatures felt to 6 and 7°C) during the 10 days preceding the cyanobacteria bloom (Fig. 2). The surface-water temperature, measured at the time of sampling along the nearshore blue-green bloom, was 14.4°C across all four measurement points.

3.2. Hydrochemistry

Hydrochemical data have been collected annually since 2014 in the nearshore area of Bol'shye Koty Bay during the summer (data of I.V. Tomberg, LIN). Long-term dynamics (2014–2019) show a drop to the minimal values of the nutrients (mostly below detection limit) in July–August, induced by the consumption of mineral nitrogen and phosphorus by phytoplankton in the nearshore zone of the bay, similar to the entire lake (Table 1). As shown in Table 1, the station 3 significantly differs from the other stations 1 and 2 by ammonium and nitrate nitrogen concentrations, which could indicate less intensive anthropogenic pressure at this station because the Baikalian pure waters always contain trace concentrations of these ions (Votintsev et al., 1975; Khodzher et al., 2017).

The chemical composition of the water collected on the 24th of July 2019 did not deviate from the long-term average reports—only trace quantities of ammonium ions, nitrates and phosphates were registered in the nearshore waters (Fig. 3). In the vicinity of the field station of LIN, the concentrations of nitrates were slightly higher (0.12 mg L^{-1}), due to the effect of the small Zhilishche River running into the lake 50 m north of the LIN station. The concentration of silicon here was also higher (0.84 mg L^{-1}), as compared to the water near the university station (0.53 mg L^{-1}).

The samples collected on the 31st of July during the cyanobacterial bloom showed concentrations of phosphates, ammonium and nitrates to be much higher than those registered a week before (Fig. 3). We observed that a heavy rainfall on the 26–29th of July 2019 may have caused such changes in the chemical composition of the lake water. During this period, over 51 mm of precipitation was reported, making up half the monthly norm of July. Showers washed away large quantities of soil organics and, likely, domestic wastes from non-isolated septic tanks of the neighbouring buildings. The rains also affected the inflow of nitrogen, phosphorus and silicon.

Chemical analysis of the rainwater showed the possible source of nutrients to the lake (Table 2). The phosphate concentration in the rainwater reached 0.131 mg L^{-1}, nitrates up to 3.65 mg L^{-1}, and ammonium 10 mg L^{-1}. The noteworthy indications of source for these nutrients are the high concentrations of potassium (up to 0.64 mg L^{-1}) and sulphates (up to 8.53 mg L^{-1}) and extremely low pH values (3.93–4.77). The atmosphere was evidently contaminated at the time by large-scale forest fires registered in the Krasnoyarsk Region and to the north of the Irkutsk Region. The rise of nitrate (0.31 mg L^{-1}) and silicon concentrations (1.41 mg L^{-1}) near the LIN station, possibly, was a consequence of excessive inflow of river water raised after rain.

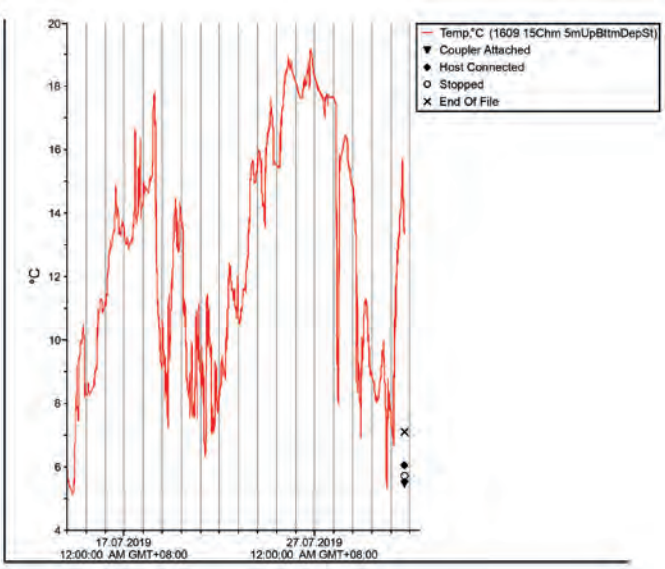

Fig.2. Water temperature near the bottom at a depth of 3 m, a fragment of a plot showing the dynamics of water temperature 10 days before the bloom.

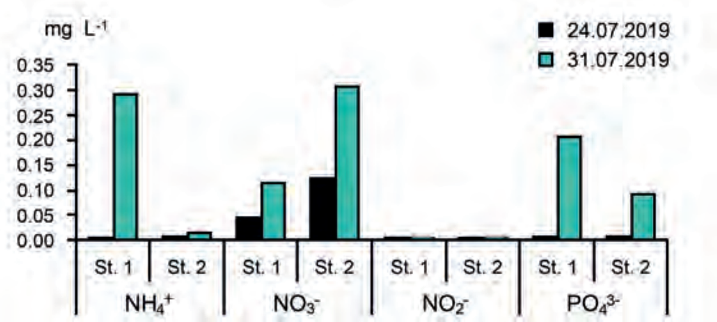

Fig.3. Concentration of nutrients in the water near the shore of Bol'shye Koty Bay in July 2019 at Site 1—the biological station of Irkutsk State University—and Site 2—field station of Limnological Institute SB RAS. Although replicate sampling for nutrients was not conducted, extensive sampling before and after the work reported here shows that coefficients of variation for lake water nutrient analyses are typical <10% with high values ranging to 20% (Khodzher et al., 2017; Tomberg et al., 2012).

Table 1. Long-term average concentrations of nutrients (mg L^{-1}) during July–August 2014–2019.

	NH_4^+	NO_2^-	NO_3^-	PO_4^{3-}	Si
			C ± S, mg L^{-1}		
Site 1	0.009 ± 0.008	0.003 ± 0.002	0.05 ± 0.02	0.009 ± 0.007	0.38 ± 0.13
Site 2	0.011 ± 0.009	0.002 ± 0.002	0.11 ± 0.06	0.007 ± 0.004	0.50 ± 0.33
Site 3	0.005 ± 0.005	0.001 ± 0.001	0.04 ± 0.02	0.009 ± 0.002	0.41 ± 0.14

C: average concentration; S: standard deviation.

Table 2. Elemental composition of precipitation in 2019 in Bol'shye Koty Settlement (station of Limnological Institute SB RAS).

Date	N	NO_3^-	NH_4^+	PO_4^{3-}	SO_4^{2-}	K^+	$\Sigma_и$	pH
		C±S, mg L^{-1}						
26.07.2019	1	1.01	0.43	0.131	2.13	0.14	5.2	4.53
27.07.2019	5	1.20 ± 1.04 (2.88)	0.77 ± 0.65 (1.72)	0.034 ± 0.027 (0.069)	2.93 ± 2.09 (6.11)	0.06 ± 0.05 (0.14)	5.8 ± 4.6 (13.0)	4.45 ± 0.36 (4.03)
28.07.2019	4	0.57 ± 0.20 (0.57)	0.47 ± 0.33 (0.95)	0.012 ± 0.007 (0.021)	2.13 ± 0.76 (3.06)	0.03 ± 0.01 (0.05)	3.6 ± 1.1 (4.6)	4.38 ± 0.10 (4.27)
29.07.2019	2	2.28 ± 0.47 (2.61)	3.62 ± 3.49 (6.1)	0.018 ± 0.010 (0.026)	5.10 ± 1.23 (5.97)	0.16 ± 0.01 (0.16)	11.9 ± 5.3 (15.6)	4.01 ± 0.04 (3.98)
30.07.2019	1	3.65	10.1	0.012	8.53	0.64	24.1	4.33

N: number of samples collected per day; Σ_i: sum of ions; C: mean daily concentration; S: standard deviation; maximal concentrations observed in a day mentioned in brackets.

3.3. Plankton

On the 24th of July 2019, the surface water in the nearshore zone of the bay was clear, whereas on the 31st of July, after four days of continuous showers that caused the rise in nutrient concentrations (Fig. 3), we observed massive abundance of cyanobacteria (Fig. 4). Substantial amounts of cyanobacteria were observed along the shoreline between the field station of LIN in the south and a pier of the Research Institute of Biology in the north. Maximal blooms were registered opposite the hostels of the Institute and University which were visited by approximately 200 people in the two weeks before the study. The distance from the water's edge to the housings was about 20–30 m. The shoreline zone in Bol'shye Koty Bay north and south of these buildings was free of the visible blooms of nuisance cyanobacteria. The cyanobacteria formed a solid stripe 1–1.5-m wide and approximately 1-km long adjoining the water's edge, reducing the transparency of water to 20–30-cm depths. The day after, on the 1st of August (windless, sunny, no more rain), visual observations revealed no cyanobacterial masses along the shoreline area. An expedition of microbiologists collecting samples on the 13th of August found these cyanobacteria deep in the water nearly 15 m away from the shore.

Microscopic analysis of the "blooming" organisms revealed massive abundance of *Dolichospermum* cyanobacteria during collection, with a dominance over 98% of the total abundance of *D. lemmermannii* (Fig. 5). The concentration of *Dolichospermum* along the shore of the bay varied from 7.2–71.9 thousand cell mL^{-1} and biomass 0.73–7.20 g m^{-3}. Maximal concentration was recorded at the site opposite the canteen of the University Biological station, with a minimum at Site No. 3 at the northern end of the bay (Fig. 1). The maximal abundance and biomass in this case were higher than those reported by Popovskaya (1991) at the end of 1980–90s, 30 thousand cell mL^{-1} and 3–6 g m^{-3}, respectively. The colonies included actively dividing cells, heterocysts and akinetes, i.e. cyanobacteria were not at the initial but a mature vegetation stage. These colonies were densely covered by attached ciliates of the genus *Vorticella*, their abundance varying from 10–20 cells mL^{-1} indicating the bloom was likely terminating.

3.4. Saxitoxins

Saxitoxin-producing genes were present across all samples under this study, as shown by the PCR screening with *stx*A-gene primers. The concentration of saxitoxin in the water samples collected on the 31st of July was 0.45 ± 0.05 μg L^{-1} and 0.025 ± 0.01 μg L^{-1} on the 13th of August, respectively. Saxitoxin content in cyanobacteria cells (intracellular) was 7.900 ± 200 μg g^{-1} of dry weight.

4. Discussion

Notwithstanding that cyanobacteria are common inhabitants of shallow, warm, calm and eutrophicated waters, their recent mass development in many large lakes and water reservoirs of the world has become a matter of deep concern for the research community due to their ability to produce toxins that are hazardous to human and animal health (Paerl et al., 2001; Sitoki et al., 2012; Ho and Michalak, 2015; Korneva, 2015; Kurashov et al., 2018; Sterner et al., 2020). For example, Lake Erie suffered from a burst of cyanobacterial bloom, leading to an extension of dead zones at the lake bottom, a decrease in fish populations and the contamination of beaches, negatively affecting the local tourism industry (Ho and Michalak, 2015; Chaffin et al., 2019). High microcystin was registered in the drinking water of Toledo City, Ohio, located at the shallowest of Lake Erie after a cyanobacteria bloom in the municipal water supply system (Ho and Michalak, 2015). The cause of this massive cyanobacterial growth was the discharge of phosphorus into the lake from agricultural fields and municipal sewage treatment plants. Lake Erie receives the largest loading of phosphorus than any North American Great Lakes. As a result, the residents of Toledo (over 200.000) were prohibited from using tap water for domestic needs and had to buy bottled water.

Cyanobacterial blooms are often associated with eutrophic environments, but they sometimes occur in oligotrophic, for example, in Lake Superior, there have been observed *Dolichospermum* blooms along the southern shoreline, a region where human recreational contact often is high (Sterner et al., 2020). In oligotrophic Lake Baikal over the last decades, investigators have attributed the cyanobacteria encountered not only in bays and shallows as well as the pelagic zone of the lake to the dominant forms of the summer plankton population (Izmest'eva, 1988; Popovskaya, 1991; Belykh and Sorokovikova, 2003; Belykh et al., 2006; Bondarenko, 2009). Picoplankton of the genera *Synechococcus* and *Synechocystis* are among principal primary producers in the summer pelagic zone, and their abundance often reaches several billion per litre. According to the white disc test, the water transparency drops to 3.5–5.0 m in summer which is its annual minimum (Bondarenko, 2009). In years with warmer water and the absence of storms, these species are joined by the representatives of *Dolichospermum*, first by *D. lemmermannii*, the abundance of which sometimes attains millions of cells per litre. The blooms are most frequently observed in Selenga shallows, the nearshore shallow areas of the northern lake basin, and some adjacent locations in the middle and southern basins (Bondarenko, 2009).

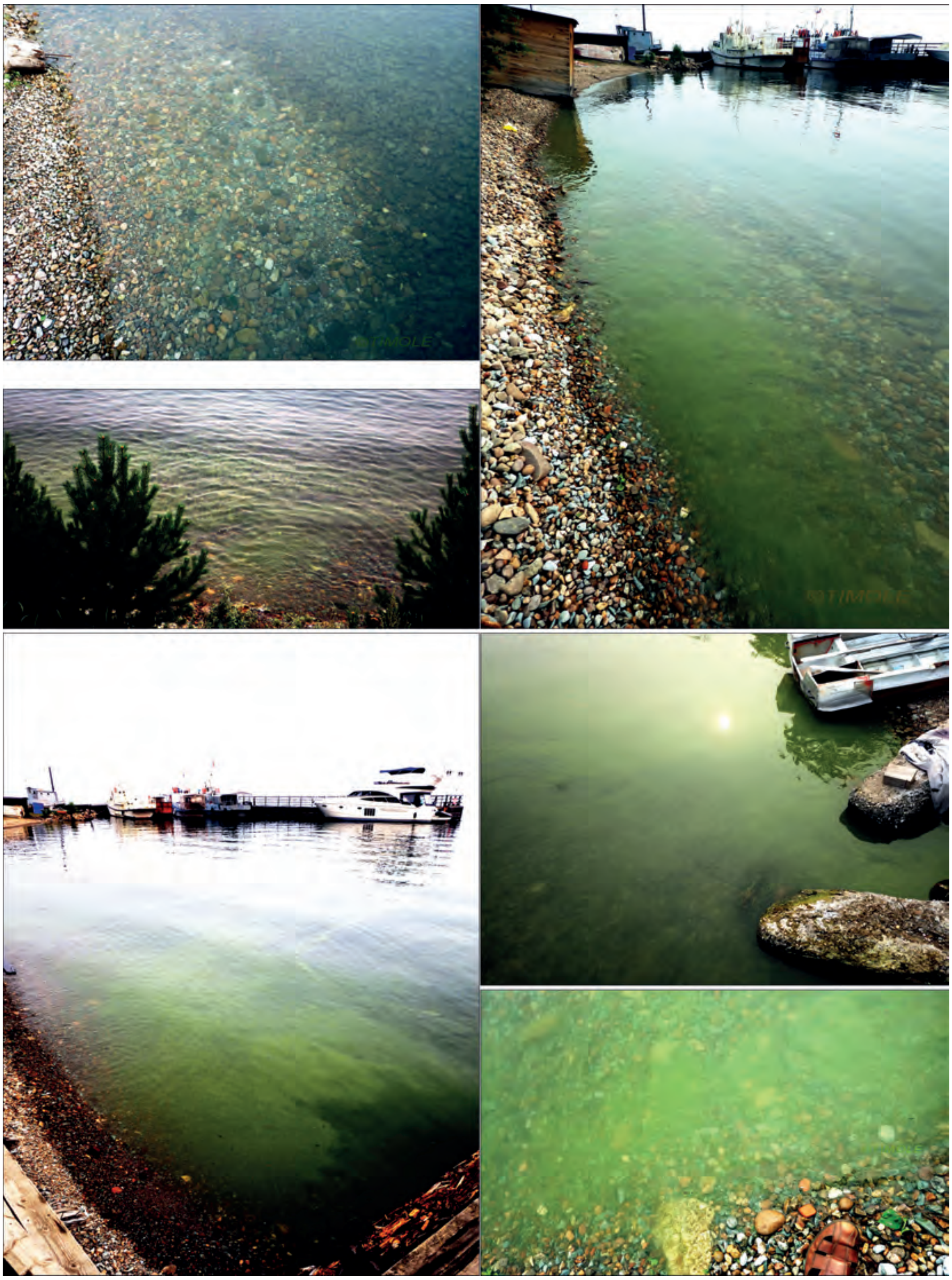

Fig.4. Nearshore area of Bol'shye Koty Bay in summer 2019: free of *Dolichospermum lemmermannii* bloom (slightly northeastern of Station 1; left upper photo) and within the bloom (photo images consequently made from Station 1 to Station 2).

Thus, an intriguing question arises: What was the triggering point for the cyanobacterial bloom in Bol'shye Koty Bay in 2019? Some researchers consider the blooming of cyanobacteria in the open parts of Baikal to be a consequence of wind activity (Kozhova, 1959; Votintsev et al., 1975; Popovskaya, 1991) that induced a transfer of the algae from the shallow-water areas, particularly Selenga shallows, Istok Sor and Proval Bay, to other lake regions. It is suggested that cyanobacterial masses in the coastal area of Bol'shye Koty Bay in July 2019 migrated from Selenga River, Maloe More Strait shallows and other places with winds or currents flowing along the shoreline. According to Antipova (1974), Bondarenko et al. (2012) and our personal data, in 1947–2018, the concentration of the algae in Bol'shye Koty Bay did not exceed 5–10 cells mL^{-1} in summer; but on the 31st of July 2019, their abundance was 7.2–71.9 thousand cells mL^{-1}. Thus, one can easily state that the time taken for cyanobacterial masses to develop in this bay, starting from the initial quantity and considering a cell division rate of 1 to 2 per day (Votintsev et al., 1975; Bondarenko, 2009), might vary from 3.3 to 8.9 days. It seems likely that, for a short period, the nearshore zone was populated by *D. lemmermannii* masses with the initial concentration of 5–10 cells mL^{-1} under favourable conditions; in other words, extensive growth of cyanobacteria started there, in the bay. In this context, it would be interesting to know the factors that may have influenced their initiation and growth.

Higher temperature is regarded as one of the driving forces of intensive cyanobacterial development (e.g. Hickel, 1988; Briand et al., 2002; Jann-Para et al., 2004; Belyakova et al., 2006; Bondarenko and Shchur, 2007; Ecology of cyanobacteria…, 2012; Korneva, 2015; Salmaso et al., 2015). Ecologic plankton surveys undertaken in the water bodies and channels of East Siberia confirm this fact. Reports on the blooms in low-mineralised (total ions 36–80 mg L^{-1}) mountain and high mountain lakes of the region upon the warming of surface waters in the summer provide us with convincing evidence of the thermal effect on cyanobacteria production (Bondarenko and Shchur, 2007). On the other hand, the largest annual biomass of cyanobacteria was observed in September–October in the lakes around Baikal when the water temperature dropped from 21°C to 6°C (Bondarenko and Shchur, 2007). In January–February, intensive winter vegetation of cyanobacteria in these nearshore lakes shows that the water temperature is an important but not exclusive factor affecting their quantitative characteristics (Bondarenko and Shchur, 2007). This is

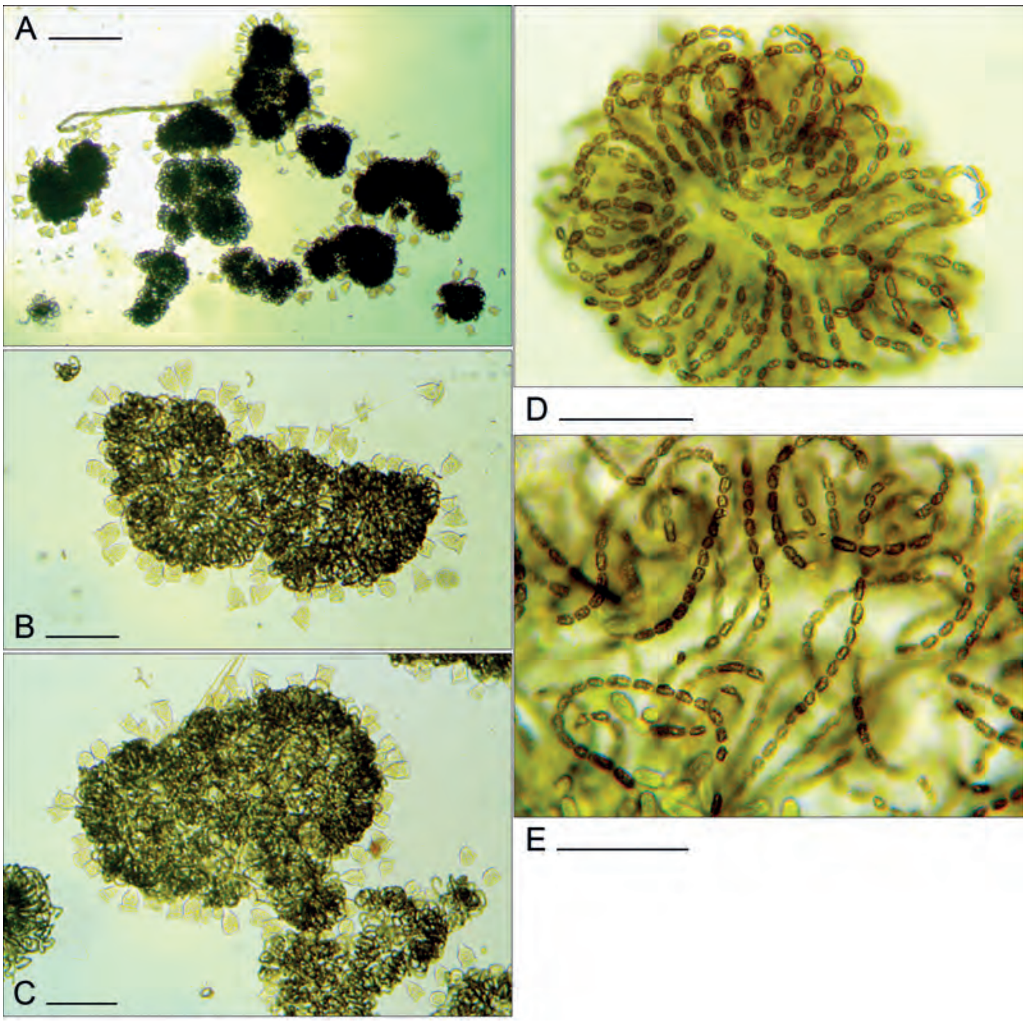

Fig.5. External view of *Dolichospermum lemmermannii* from the coastal zone of Bol'shye Koty Bay. Scale bars: A—0.30 mm, B–C—0.16 mm, D–E—65.4 µm.

also confirmed by the large diversity and abundance of cyanobacteria in lakes of Yakutia (Komarenko and Vasilyeva, 1975), Taymyr (Ermolayev, 1974) and other lakes of the Extreme North (Osobennosti struktury…, 1994).

According to the available data, including the above-mentioned cases of patchy blooms of *D. lemmermannii* in the open pelagic zone of Baikal, water warming and higher temperatures in calm windless weather, indeed, should be considered as one of the driving forces for this species' mass growth, but barely the leading one. The air and bottom-water temperatures in Bol'shye Koty Bay were very high 10 days before blooming, while the last few days after the bloom were calm. Cyanobacteria started to develop on the 28th and 29th of July when the temperature of the upper-water layer decreased to 14.4°C due to heavy rain. But warm and stable temperature conditions of surface water may positively affect the harmful cyanobacterial bloom.

Water "blooms" in well-warmed shallow water bodies caused by cyanobacteria are also considered to be related to nutrient enrichment during vegetation (Hickel, 1988; Osobennosti struktury…, 1994; Briand et al., 2002; Jann-Para et al., 2004; Belyakova et al., 2006; Bondarenko and Shchur, 2007; Ecology of cyanobacteria…, 2012; Salmaso et al., 2015), particularly with higher concentrations of nitrogen and phosphorus as reported in this paper. Long-term dynamics of the nutrients analysed using the data obtained in this investigation as well as published (Votintsev et al., 1975) evidence that concentrations of phosphates (up to 0.200 mg L^{-1}), ammonium (up to 0.29 mg L^{-1}), and nitrates (up to 0.31 mg L^{-1}) registered in the nearshore lake water on the 31st of July 2019 were in 3 to 30 times higher than average long-term concentrations. Bol'shye Koty Settlement located at the bay shore is not equipped with centralised sewage treatment utilities or isolated septic tanks, inevitably leading to increase in nutrients in the coastal waters, especially in summer when the number of visitors is high. These nutrients would be supplemented by the extra inflow of nutrients, mainly nitrogen and phosphorus, from the heavy and continuous four-day rainfall in July 2019. These heavy rains promoted the nutrient load to the lake. Maximal concentrations were confined to the area near the water's edge, which receives the flow of surface and ground waters enriched by nutrients (Fig. 3; Table 2). It seems hard to find another reason, if any, for the cyanobacterial bloom precisely in the water's edge zone 0.2–0.5m deep after four days of calm but rainy weather.

We suggest that the polluted waste waters were the main source increasing ammonium and phosphate concentrations in the nearshore zone at the University station because ammonium and phosphate were usually detected as traced elements in such waters. This is also confirmed by the data obtained in 2016–2018 during studies at the LIN field station in the same bay (Timoshkin et al., 2018). High concentrations of nutrients like those observed in the ground (lysimeter data) and interstitial waters of the beach were found. Convincing evidence has been provided for the contamination being a result of the continuous inflow of domestic waste waters from the non-isolated sewage pits of the station household, bringing about the mass development of benthic *Spirogyra* (morphotype 1), which is known as an indicator of water pollution of Baikal in the area of underwater discharge of contaminated ground waters. The hydrochemical indicators of the nearshore waters were not different from those given in the long-term average data. It is interesting to note that the heavy rains during the period preceding the bloom also contributed to the accumulation of ground water in lysimeters and the contamination of interstitial waters in summer 2016.

Along with the environmental factors affecting the harmful freshwater cyanobacteria bloom, we should consider the sensitivity of some cyanobacterial forms to mechanical effects, such as waves, turbidity, etc. During our surveys, we observed the same situation: *D. lemmermannii* masses disappeared from the shore area on the 1st of August, after a strong night wind; however, cyanobacteria were still occurred in the water until at least the 13th of August.

Blooms of saxitoxin-producing cyanobacteria in the littoral part of Bol'shye Koty Bay led to the occurrence of saxitoxins in the water, with concentrations up to 0.45 ± 0.05 μg L^{-1}. A dominant *D. lemmermannii* species was apparently the producer of saxitoxin. As early as 2010, ELISA and *stx*A-gene sequencing showed that *D. lemmermannii* was responsible for synthesis of saxitoxins in the littoral zone of eastern coast of Lake Baikal in the vicinity of Turka Village (Belykh et al., 2015a).

The presence of saxitoxins in the lake waters of Finland and Denmark was related to *D. lemmermannii* activity because the saxitoxin-positive phytoplankton samples included 95–100% of this species (Lepisto et al., 2005; Rapala at al., 2005). *D. lemmermannii* blooms in Scandinavian lakes appeared to be one of the most toxic among the cases registered, maximal STX (1.070 μg L^{-1}) concentrations were observed in an oligotrophic lake (Rapala et al., 2005). STX concentrations reported in Lake Baikal were much lower than the minimal values registered in Finnish lakes. It should be noted that the analytical kit used for saxitoxin identification had 0.6–29% cross-reactivity with the analogues: dcSTX, neoSTX, dcneoSTX, GTX2,3, dcGTX2,3, GTX-5B, sulfoGTX1,2 and lyngbyatoxin variants, therefore, the samples under this study might contain the above-mentioned paralytic toxins of molluscs. Earlier, MALDI-TOF analysis allowed us to identify several saxitoxin variants in Lake Baikal (Barguzin Bay and Malye Ol'khonskiye Vorota Strait) and reservoirs on the Angara River (Irkutsk, Bratsk and Ust'-Ilimsk) (Belykh et al., 2015b).

Countries with widespread harmful toxic blooms that are hazardous to human health have introduced national guidelines for water use. In New Zealand, Australia and Brazil, the maximum permissible level for drinking water is 3 μg L^{-1} (Current approaches…, 2012). In the shore area of Bol'shye Koty Settlement, the concentration of saxitoxin in the water (0.45 ± 0.05 μg L^{-1}) was below the threshold for drinking and recreational water usage. Our latest observations showed lower saxitoxin concentration in the water samples from Lake Baikal. Their maximal concentration registered in 2010 in Middle Baikal was 1.93 ± 0.64 μg L^{-1} (Belykh et al., 2015a). In Maloe More Strait, the concentrations were more similar to those reported here (0.59 ± 0.2) (Belykh et al., 2015b).

A complex set of environmental and anthropogenic factors, such as weather conditions and maximal recreational activity during the period of studies, were found to be involved in the mass development of *D. lemmermannii* in the open part of Bol'shye Koty Bay. This indicates the urgent need of establishing federal regulations on sewage treatment in small nearshore settlements, which are overpopulated during peak tourist season, providing for the lowest possible contamination of the open part of Baikal by untreated household and municipal wastes.

Moreover, our recent findings suggest that the current contribution of heavy precipitation to the late summer (period of maximal warming of the water in the littoral zone of Lake Baikal) in East Siberia combined with other favourable environmental factors might possibly trigger more widespread proliferation of toxic cyanobacteria not only in Bol'shye Koty Bay but also throughout the entire lake perimeter, eventually reaching the pelagic zone. Similar situation was in the large oligotrophic Lake Superior, the most pristine of the Laurentian Great Lakes. In the past decade, there have been observed *Dolichospermum* blooms (Sterner et al., 2020). The two largest of them, in 2012 and 2018, occurred during years of especially extreme rainfall which provided nutrients or living propagules to the blooms from the watershed. The authors consider, if these newly observed blooms are indeed driven by temperature and rainfall as this evidence suggests, blooms may continue.

As far as our present investigation of the harmful toxic cyanobacterial blooms in the coastal zone of Lake Baikal is concerned, we realise how vulnerable this unique water body is because it shelters endemic flora and fauna and holds 20% of the world's non-frozen fresh water reserves, while 2.7 billion people experience water scarcity. Finally, the obtained results, regretfully, provide one more evidence of current negative ecological changes in coastal biota of Lake Baikal.

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Conflicts of 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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Actual inflow of riverine sediment load into Lake Baikal: main tributaries – the Selenga, Upper Angara, and Barguzin Rivers (Russia)

Potemkina T.G.*, Potemkin V.L.

Limnological Institute of the Siberian Branch of the Russian Academy of Sciences, Ulan-Batorskaya str., 3 Irkutsk, 664033, Russia

ABSTRACT. The sediment load delivery into Lake Baikal from its main tributaries – the Selenga, Upper Angara, and Barguzin Rivers has been reduced since the mid-1970s. This is explained by climate change and socioeconomic activities. Integrated analysis of changes in hydro-meteorological parameters (water discharge, sediment load, air temperature, precipitation) and their trends over the period 1946–1975 (baseline) and 1976–2017 (warming) is performed. Changes in natural processes and human activity were negligible during the baseline period. During the warming period, the greatest reduction of the sediment load inflow against the background of temperature rise and precipitation decrease occurred in the interval between 1996 and 2017 in the Selenga River, between 1985 and 2017 in the Upper Angara River, and between 1992 and 2017 in the Barguzin River. The flux of the sediment load into these rivers was 768×10^3, 88×10^3, and 29×10^3 t y^{-1}, respectively. This is 2–3 times less than the average multiyear values for all period of 1946–2017, which are usually used when characterizing sediment load runoff from these rivers. Currently the values in the given intervals correspond to the actual sediment load flux into Lake Baikal from the main tributaries.

Keywords: sediment load flux, Selenga River, Upper Angara River, Barguzin River, Lake Baikal

1. Introduction

The river fluxes affect the morpho-lithodynamics of the shore zone, its ecological state, sedimentation processes, and the health of the aquatic ecosystem of water bodies. The sediment loads play a crucial role in these processes, as they are able to accumulate and transfer various substances into water bodies. Currently, significant changes in the sediment load occur in many large rivers of the world. In general, the sediment load of many rivers diminished and, therefore, its inflow into water bodies decreased (Syvitski, 2003; Walling and Fang, 2003; Milliman et al., 2008). The decrease of sediment load supply into water bodies and its consequent impact on their aquatic and coastal systems have become a global topic (e.g., Dai et al., 2009; Wang et al., 2011; Lu et al., 2013; Zhao et al., 2015; Timpe and Kaplan, 2017; Dorjsuren et al., 2018). A decrease of the sediment load for the main tributaries of Lake Baikal – the Selenga, Upper Angara, and Barguzin Rivers, which bring the main volume of sediments to the lake, is also observed. The river sediment load runoff in Lake Baikal basin is defined by the interaction of a number of natural factors (relief, ruggedness and composition of rocks, type of soils and vegetation, weathering, and climatic conditions), as well as by anthropogenic activity.

At present, a special attention is paid to the ecological state of Lake Baikal and its shallow zone because of local negative ecological processes observed there, for example, blooms and increase of productivity of toxin-producing cyanobacteria and filamentous algae, disease of endemic Baikal sponges – a natural filter of the lake water, a fecal pollution of the shore waters, etc. (Timoshkin et al., 2016). These negative processes are likely connected with both climate changes and human activities (Potemkina et al., 2018). Therefore, the preservation of the world's largest lake – Baikal, containing about 20% of freshwater reserves of the world, the natural UNESCO World Heritage Site, requires a better understanding of the current trends in the natural processes and ecology, including the river runoff.

The catchments of the main tributaries – the Selenga, Upper Angara, and Barguzin Rivers – occupy more than 90% of the total catchment of Lake Baikal. The long-term data on their water and sediment load runoff characterize natural and anthropogenic changes in almost all territory of the lake basin. Usually, the sediment load runoff is characterized by an average value over all monitoring period. However, at present, this value differs from the actual sediment load supply into Lake Baikal. Therefore, this study is aimed: (1) to detect periods of temporal changes of the sediment

*Corresponding author.
E-mail address: tat_pot@lin.irk.ru (T.G. Potemkina)

load in the context of the climate and anthropogenic changes; and (2) to assess the actual sediment load supply from the main tributaries into the lake. The results of the study may be important for investigating processes related to hydrology, geomorphology, biogeochemistry, sedimentology, pollutant supply and ecology in the tributaries-Lake Baikal system. They are of relevant interest for other freshwater lakes in the world, too.

2. Materials and methods

We have analyzed long-term observation series of hydro-meteorological data (water discharge and sediment load, air temperature and precipitation). The long-term hydro-meteorological parameters cover the period from 1946 to 2017. The long-term hydrological data were obtained from the Hydro-meteorological Centre of Russia (Roshydromet). The long-term meteorological parameters (air temperature and precipitation) for the river basins were received from the NCEP/NCAR (The National Centers for Environmental Prediction/The National Centre for Atmospheric Research) global reanalysis database, which is accessible on the ESRL (The Earth System Research Laboratory) website (https://www.esrl.noaa.gov/). They are available in NetCDF (Network Common Data Form) format. The original data were the average monthly air temperature values with a regular grid step of $2.5 \times 2.5^{\circ}$ and monthly average precipitation values with a grid step of $1 \times 1^{\circ}$. For the further analysis, the data on the average monthly precipitation intensity were converted into the total precipitation per month.

Statistical methods were used to examine the relationships between the hydro-meteorological parameters and their tendencies (trend analysis, pair correlation, linear-trend coefficients). The non-parametric Mann-Kendall (M-K) test allowed determining the significance of a trend, which was considered to be significant at the $p < 0.05$ level. In addition, the M-K rank statistics and cumulative anomalies method (Feidas et al., 2004; Zhao et al., 2015) made it possible to detect the beginning of changes in the hydrological parameters of rivers.

Study area

The studied tributaries – the Selenga, Upper Angara, and Barguzin Rivers (the largest by water runoff and sediment supply) – are situated on the eastern shore of Lake Baikal. The Baikal tributaries bring about 60 km^3 of water into the lake annually, among them the studied tributaries account for 27.2, 8.48 and 3.82 km^3 y^{-1}, respectively. These rivers are the main sources of river sediment load as well: the Selenga River – 1535×10^3 t y^{-1}, the Upper Angara River – 243×10^3 t y^{-1}, the Barguzin River – 90×10^3 t y^{-1}. The values are the mean annual water runoff and sediment load supply of main tributaries for the period of 1946–2017.

The catchments of the main tributaries are located in different natural conditions. The main general characteristics of the natural conditions in the basins of these rivers are an extremely continental climate and the presence of permafrost. There are significant differences, too. The drainage basins of the Upper Angara and Barguzin Rivers are framed by mountains and have a moderate humidity. The Selenga River drainage basin extends far southwards, to areas experiencing a moisture deficit (forest-steppe, steppe and desert areas). The main feeding sources of the Selenga and Barguzin Rivers are rain and melt waters with approximately equal contribution. Melt water is a typical feeding source of the Upper Angara River (Resursy…, 1973). The mouth areas of three main tributaries belong to different hydro-morphological types. The mouth area of the Selenga River is an open multi-arm advancing delta. The mouth area of the Upper Angara has a semi-closed delta that is formed in lagoon separated from the lake by a coastal bar. The Barguzin River has a delta-free one-arm mouth area. Water and sediment load enters directly the Barguzin Bay, which goes far into the shore.

3. Results and discussion

The hydrolithodynamics and ecology of the Baikal shore zone and of Lake Baikal mostly depend on quantity and quality of substances and pollutions supplied by main tributaries. Herewith, an essential importance in this issue belongs to river sediment loads (Chalov et al., 2016; 2018). The global warming recorded since the mid-1970s led to changes in the regional hydro-meteorological parameters and natural processes in the river catchments, including the sediment load. In addition, socioeconomic activities also contributed to the changes in the sediment load. Moreover, at present, negative ecological processes in the shallow zone of Lake Baikal are observed (Timoshkin et al., 2016). Therefore, it is very important to assess the actual sediment load supply into Lake Baikal from its main tributaries in the context of the climate instability and anthropogenic pressure for monitoring the ecological state and hydrolithodynamics of the lake and its shore zone.

An integrated analysis of changes of hydro-meteorological parameters, their values and trends during the monitoring period was performed. The period of 1946–2017 was divided into two: 1946–1975 (baseline) and 1976–2017 (warming) periods. Changes in natural processes and anthropogenic pressure were negligible during the baseline period, whereas they considerably increased during warming period. During the baseline period, the sediment load fluctuations were in general synchronous to the water discharge fluctuations, i.e., the sediment load dynamics was determined by hydro-climatic factors. During the warming period, this synchronization was broken.

The average temperature has risen by +1 °C in the river basins over the warming period having a statistically significant trend according to the M-K test. A decrease of precipitation (2–9%) in the river basins was observed during 1976–2017. Against the background of the increasing temperature and decreasing precipitation, the water discharge has a slightly negative trend (5–13%) for the Barguzin River and the Selenga River and a slightly positive trend (2%) for the Upper Angara River. However, the sediment load has decreased greatly (53–72%) since the beginning of the warming period (Table) and has a statistically significant trend according to the M-K test. Obviously, there are other processes caused by the warming and human activities. The main ones are permafrost degradation, changes in atmospheric circulation, evapotranspiration, soil erosion, upward movement of vegetation in mountainous areas, weathering of rocks, etc. (Törnqvist et al., 2015; Kasimov et al., 2017). Socioeconomic activities (changes in the agriculture, land use, various mining activities, construction of roads, urbanization, etc.) also contributed to the sediment load decrease.

The use of the M-K rank statistic and cumulative anomalies method made it possible to detect the beginning and the intervals of changes of the hydrological parameters during the warming period and to clarify the actual sediment load supply into Lake Baikal. The statistical methods showed that the sediment load changes had begun since 1976 and their greatest decrease had occurred in the Selenga River over the interval 1996–2017, in the Upper Angara River over the interval 1985–2017 and in the Barguzin River over the interval 1992–2017 (Fig. 1). For these intervals, the water discharge in the Upper Angara and the Barguzin Rivers changed little in contrast with the baseline period (Fig. 2). In the Selenga River, the water discharge decreased by 26% in 1996–2017 in comparison to the baseline period. It exceeds the moderate average reduction of 13% for the entire warming period. The sediment load flux of the Selenga River in the given interval was 768×10^3 t y $^{-1}$, thus being smaller than the average value for all warming period – 1048×10^3 t y $^{-1}$ (Table). For the Upper Angara River, these values were 88×10^3 t y $^{-1}$ and 119×10^3 t y $^{-1}$, for the Barguzin River – 29×10^3 t y $^{-1}$ and 49×10^3 t y $^{-1}$, respectively. Thus, the values in the given intervals correspond to the actual sediment load flux from the main tributaries into Lake Baikal. This is 2–3 times less than the average multiyear values for the period 1946–2017 (Table), which are usually used for characterizing the sediment load runoff from the main tributaries into Lake Baikal.

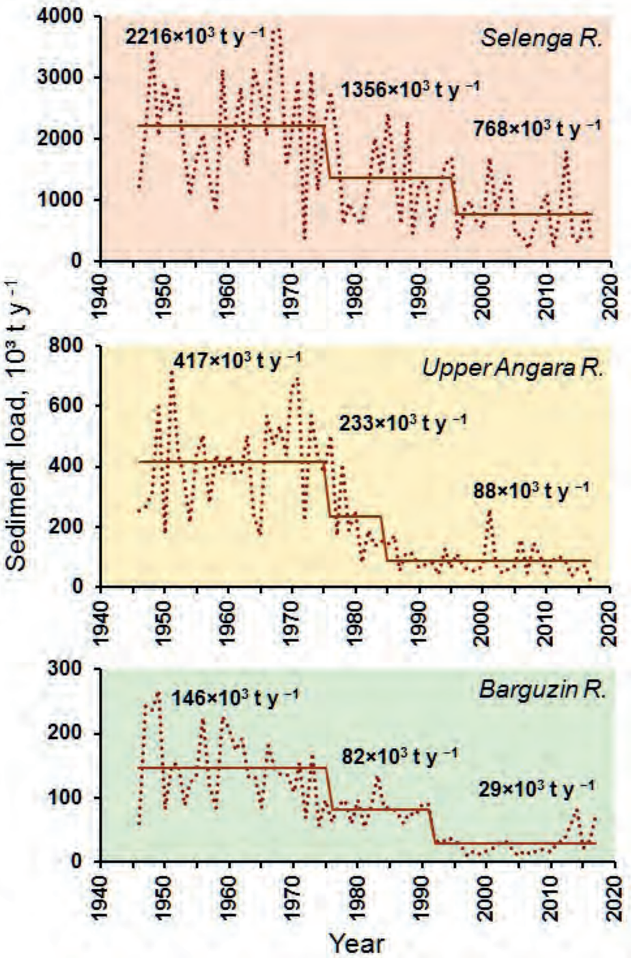

Fig.1. Actual sediment load supply from the main tributaries into Lake Baikal.

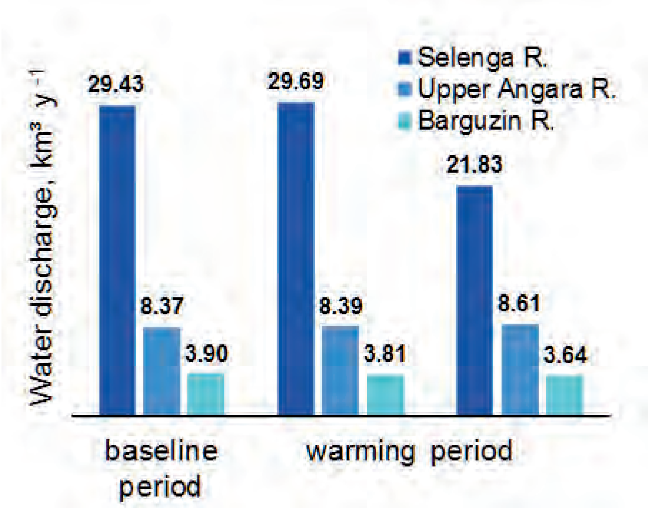

Fig.2. Changes of the water discharge at the given periods.

Table. Changes in the average annual water discharge (W, km^3 y^{-1}) and sediment load (S, 10^3 t y^{-1}) in the river basins in different periods

Period	Selenga R.		Upper Angara R.		Barguzin R.	
	W	S	W	S	W	S
1946–2017	27.18	1535	8.48	243	3.79	90
1946–1975	29.43	2216	8.37	417	3.90	146
1976–2017	25.57 (–13%)	1048 (–53%)	8.56 (+2%)	119 (–72%)	3.71(–5%)	49 (–66%)

Note. Data in parentheses indicate the relative change compared with the corresponding value in the baseline period (1946–1975); symbol '+' in the round brackets corresponds to the increase, whereas '–' represents the decrease.

4. Conclusions

The sediment load supply into Lake Baikal from its main tributaries – the Selenga, the Upper Angara and the Barguzin Rivers – has been considerably reduced since the mid-1970s. This is explained by climate change and socioeconomic activities. The statistical methods showed that the gradual sediment load decrease had begun since 1976 and its greatest reduction had occurred in the Selenga River over the period 1996–2017, in the Upper Angara River over the period 1985–2017 and in the Barguzin River over the period 1992–2017. The sediment load supply from the main tributaries into the lake during these periods was smaller than its average value for all warming period (1976–2017) and is only 35% of the baseline period (1946–1975) for the Selenga River, 21% for the Upper Angara River and 20% for the Barguzin River. Moreover, it is 2–3 times less than the average multiyear values for the period 1946–2017, which are usually used for characterizing the sediment load runoff from the Selenga, Upper Angara, and Barguzin Rivers into Lake Baikal. Thus, the values in the given intervals correspond to the actual sediment load flux from the main tributaries into Lake Baikal.

These results are important for further studies and forecast of the sediment load and pollutant supply from the tributaries into Lake Baikal, for analysis and evaluation of the ecological state and functioning of the shore zone and the whole lake. They can also be important for studying other lakes of the world that have similar natural conditions.

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Conflicts of 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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The geochronology of a palaeolake at the Pleistocene/Holocene transition in the Muya-Kuanda Basin (Eastern Siberia, Russia)

Ineshin E.M.[1]*, Ruposov V.L.[2], Buyantuev V.[3], Voronin V.I.[3], Oskolkov V.A.[3], Moritz R.A.[3], Hommel P.[4]

[1] *Irkutsk State University, Irkutsk, Russia.*
[2] *Irkutsk National Research Technical University, Irkutsk, Russia.*
[3] *SIFIBER SB RAS, Irkutsk, Russia.*
[4] *University of Liverpool, Liverpool, UK*

ABSTRACT. This article presents new data on the study of preserved wood from flooded forests in the Muya-Kuanda Basin, Eastern Siberia. On the basis of the stratigraphic position of a buried tree stump horizon, the analysis of the associated alluvial deposits and a new programme of radiocarbon dating, the chronology of formation and collapse for a Late Pleistocene palaeolake in the Muya-Kuanda Basin can be precisely determined. The accuracy of dating of geological events with the radiocarbon method and the possibility of linking them to calendrical dates is discussed. As a result of this research it is possible to connect the geochronology of the lake with archaeological sites in the Vitim Basin, both upstream and downstream along the river. The reasons for the periodic formation of substantial bodies of water in the Muya-Kuanda Basin are also discussed, with implications for decision making with regard to the modern economic development of the region.

Keywords: Flooded forest horizon, dendrochronology, palaeoclimate, dammed lake, archaeological sites, fault valley, radiocarbon dating

1. Introduction

Stump horizons are, in terms of the accuracy of the dating of geological events, one of the most valuable sources available to geochronologists. They are formed during the catastrophic (single event) flooding of forest landscapes as vegetation, including trees are buried *in situ* by a significant depth of sediment accumulating at the bottom of a rapidly forming body of water. Three remarkable examples of such horizons have been found in the Muya-Kuanda Basin and, unlike almost all other sources, they provide direct evidence for the presence of a series of dammed lakes in the Muya-Kuanda Basin, as well as evidence for the duration of each phase of flooding. These stump horizons, named after the places where they were identified correspond to different chronological periods (given in uncalibrated radiocarbon years before present (bp)): Sukhokit stump horizon – 12124 ± 25 – 11967 ± 24 bp (Sukhokit Stage), Shchuchya channel (27630 ± 385 – 27470 ± 320 bp) (Shchukin stage), Kobylin channel (34880 ± 260 – 41080 ± 500 bp) (Kobylin stage of backwater body) (Table).

The Sukhokit stump horizon, which is the subject of this article, was discovered and first studied by A.A. Kulchitsky (Kulchitsky and Orlova, 1991; Kulchitsky et al., 1997). These researchers obtained the first radiocarbon dates (via the scintillation method) for buried wood, and proposed a tectonic cause for the damming of the Param canyon and the formation of a substantial backwater lake in the chronological range 12,300 - 10,300 bp (Kulchitsky et al., 1997). However, unlike other stump horizons in the basin, which have since been revisited by a range of other researchers, the stump horizon at the mouth of the Sukhokit stream has seen no further study.

This is perhaps because researchers investigating these horizons saw them only as a way of dating the formation of particular *geological* deposits and events. There has been no comprehensive investigation of the stratigraphy of sandy deposits, the characteristics of the forest vegetation, the process of burial, or the wood remains themselves. Moreover, there has been no attempt to extract palaeoclimatic information from this valuable source or to correlate it with the of the study of archaeological remains in the Muya-Kuandinsky depression, or more broadly across the Vitim Basin. This study aims to redress this imbalance and present

*Corresponding author.
E-mail address: ineshin.evgen@yandex.ru (E.M. Ineshin)

results that begin to fill this gap in our knowledge.

2. Materials and methods

In order to obtain the maximum number of samples from the reference horizon – where the tree trunks were located in situ – we re-examined and further studied the exposure described by A.A. Kulchitsky at the mouth of the Sukhokit stream, a left-hand tributary of the Muya River (Kulchitsky et al., 1997) (Fig. 1B). This allowed us to clarify the stratigraphy of the section, to take samples for further dating of the geological events recorded in the loose deposits of the strata and obtain trunk material from which to contribute to the continuous tree-ring chronology of North Asia. An important aim of the study was to synchronise the formation of the stump horizon with other archaeological sites, both upstream and downstream along the Vitim which had been previously subjected to AMS dating. The total length of the section, exposed along the left bank of the Muya River at a height of 15-18 meters above the modern river level, is 370 meters. In this section which both the remains of the stump horizon itself and sediments associated with the ancient mouth of the Sukhokit stream were recorded.

The latter sediments, associated with the ancient mouth of the Sukhokit stream, are located 230 meters downstream from the modern mouth and 15 meters higher than its current level. and is filled with buried wood. The depth of burial of the stump horizon from the modern surface varies between 3 - 4 metres along the strike of the section and occupies a sub-horizontal position along the strike. The stump horizon itself is a buried soil of a floodplain type (black dense humus sandy loam with forest litter of twigs, leaves, moss, fallen trees), with remains of well-preserved erect tree trunks in situ (Fig. 2; Fig. 3). It varies in thickness between 3 - 7 cm along the strike and is washed out in places. The soil is overlain by dense gleyed heavy loam of gray-bluish color, interbedded with interlayers of light yellow alluvial sand. In total, 23 specimens of well-preserved trunks *in situ* were taken directly from the stump horizon, and 4 specimens of buried wood were taken from the ancient channel of the Sukhokit stream, which is epigenetic to the stump horizon.

3. Results and discussion

3.1. The structure of the sedimentary deposits and evidence of the palaeolake

The stumps of trees with a root system and a height of 0.4 - 0.7 meters observed in the section (the height of the stumps corresponds to the thickness of the overlying sands with subhorizontal or oblique bedding) are at a distance of 1 to 4 meters from each other, which corresponds almost precisely to the density of the stand of larch and spruce on the modern floodplain the Muya River. Among the recorded trunks of the stump horizon, all specimens belong to larch (*Larix sibirica*) (Fig. 3A, 3B). The wood of the preserved dark gray larch trunks is dense and well preserved. The diameter of the trunks ranges from 7 to 13 cm (Fig. 3A, 3B). The time span of the trees of the Sukhokit stump horizon covers an approximately 200-year period. The height of the stumps corresponds to the thickness of the lacustrine sands overlying the buried soil.

The well-preserved trees and forest litter between

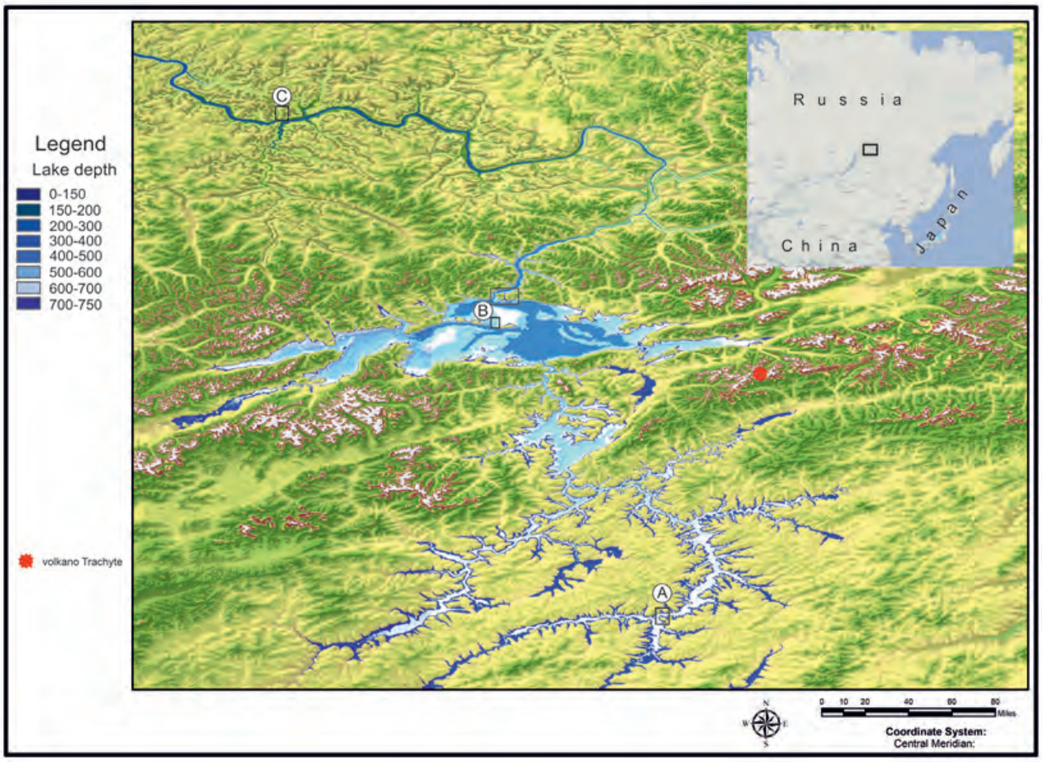

Fig.1. Map of the model of the palaeolake of the Sukhokit stage (11967 - 12124 bp). A – Ust'-Karenga archaeological complex, B - section of the stump Sukhokit horizon, C - section of the multilayer archaeological site Bolshoy Yakor I.

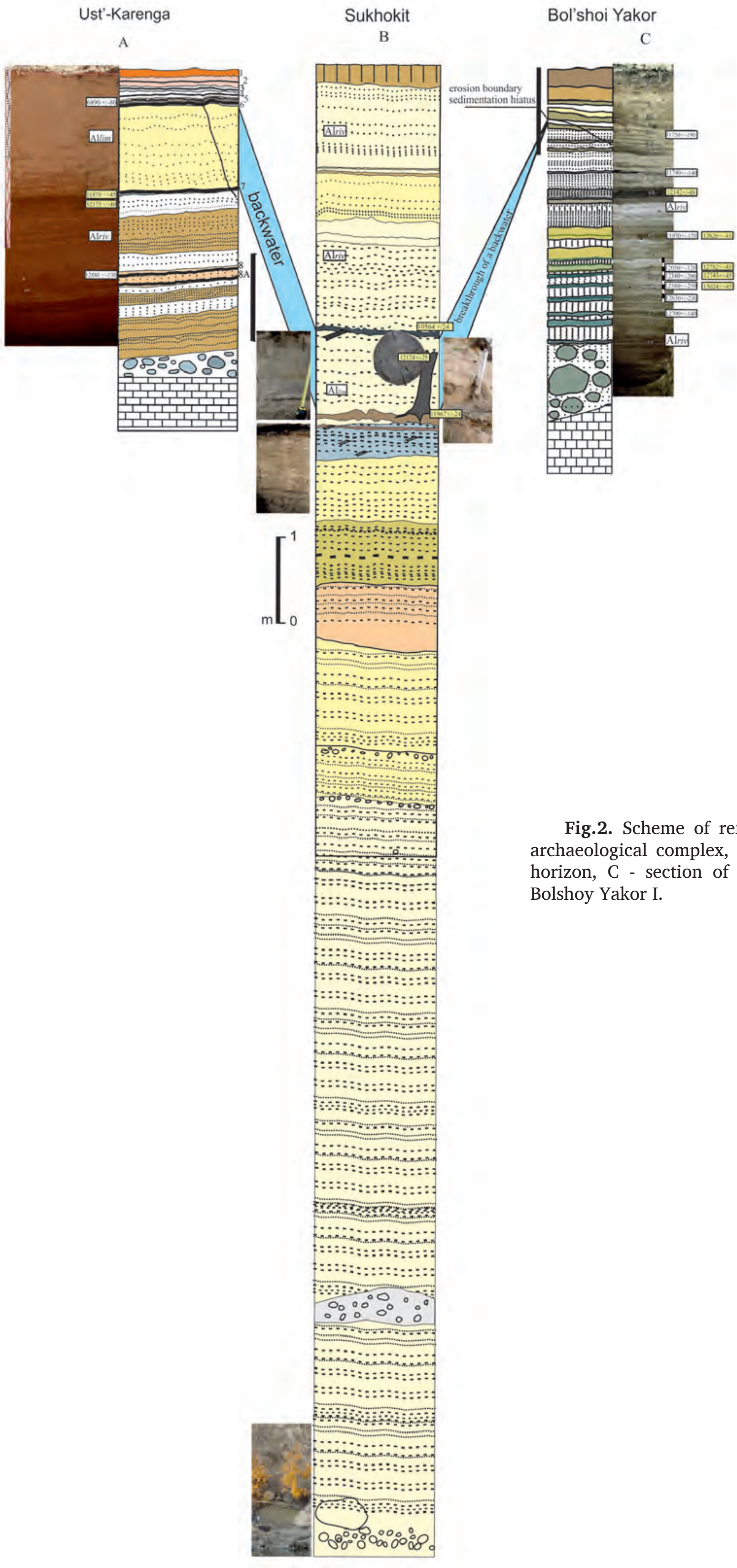

Fig.2. Scheme of reference sections: A – Ust'-Karenga archaeological complex, B - section of the stump Sukhokit horizon, C - section of the multilayer archaeological site Bolshoy Yakor I.

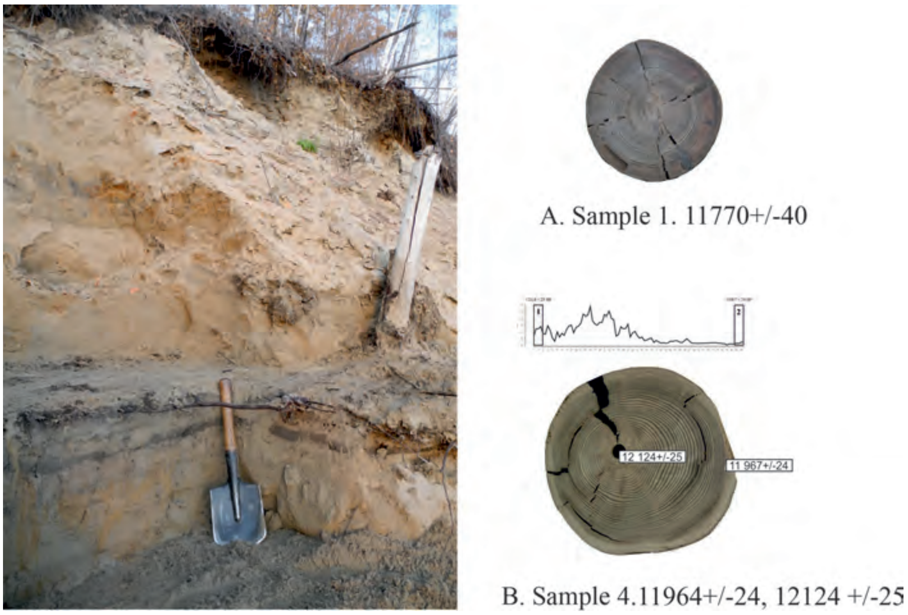

Fig.3. Cleaning of the stump horizon Sukhokit and sections of buried wood. A – Sample 1, B – Sample 4.

the trunks suggests a rapid rise in water levels and the flooding of the forest without a planar flow, which would have washed out detrital material. The rapid burial of tree trunks, their burial within dense finely dispersed sediments contributed to the isolation of the material from access to oxygen, and later, after the collapse of the palaeolake lake, the appearance of the permafrost effect contributed to the good preservation of wood and other organic matter (Fig. 3).

The following description details the stratigraphy from the section (from top to bottom) supplemented by illustrations (Fig. 2; Fig. 3).

Layer 1 – root bound soil with an abundance of organic matter up to 0.15-0.20 m thick. *Layer 2* dense silty loam layers with unclear bedding – though some charcoal bearing layers in lower part of the deposit emphasize the stratification. At the bottom, the layers are also are deformed by cryogenic processes. The thickness of the strata along the strike of the section is consistent between 1.0 to 1.30 m. *Layer 3* - yellow-gray polymict sands with interlayers of iron oxides. The sediments are alluvial in origin with varying depositional regimes from channel to floodplain facies of the river. The bedding of the strata along the strike of the section is parallel, changing to cross-bedded and channel-fill/ripple sediments. Frost wedges initiated in the upper part of the bed reach down to a depth of at least 3.5 meters. The thickness of the deposits ranges from 1.60 to 1.30 m. *Layer 4* – peaty palaeosoil (soil 2). A dense, compressed black histosol soil with poorly decomposed plant remains marking an extended period of waterlogging of the valley bottom associated with the collapse of the palaeolake lake and drainage of the bottom of the basin. The soil is saturated with the remains of woody vegetation in the form of roots, twigs, fragments of thin stems. This layer is clearly visible across the section with a variation in the thickness from 0.05 to 0.10 m. AMS-dating obtained from the remains of woody vegetation in the soil provided a date of 10564 ± 24 (SUERC-87225). This dating allows us to establish a *terminus ante quem* date for the flooding of the basin. *Layer 5* - Column greenish gray silty sands finely interbedded with silts; gleyed in the upper and lower parts with thin parallel bedding. In the middle part of the stratum, areas of dischordant bedding are noted. Lacustrine alluvium associated with the palaeolake lake. The thickness along the section is consistent, ranging from 1.05 to 1.0 m. Trunks of buried trees extend through the stratum. The root systems of these trees continue into the palaeosoil (soil 1) which underlies the deposit. The upper parts of the tree, which would have extending beyond the upper boundary of the layer, have been broken off when the wood was still relatively fresh. Other than this, the trunks of the trees are perfectly preserved: they have bark and small twigs, and on the surface of the buried soil 1, the remains of forest litter – branches of trees, shrubs, and fallen cones is preserved. Further up in the stratum, there are occasional remnants of redeposited woody vegetation in the form of fragments of branches and tree roots. *Layer 6* - dense peaty palaeosoil (soil 1). Along the strike of the section, this level is traced everywhere, although in some areas the soil is partially eroded. In a number of areas along the strike of the section, the soil is subdivided into separate humic interlayers containing organic remains alternating with gleyed bluish-gray interlayers of loam and light interlayers of fine-grained sand. Trees, almost exclusively larch (*Larix sibirica*), grew on this soil surface. The distance between trees is 1.0 to 4.0 m, the thickness of the trunks is from 0.05 to 0.25 m, the age is from 10 to 250 years. The height of the tree trunks ranges from 0.40 to 0.69 m and corresponds to the thickness of the bottom lake sediments that buried forest vegetation, which may indicate that the burial was quick and catastrophic. Soil 1 marks the level of the drained waterlogged terrace of the Muya River, which had emerged from the cycle of floodplain accumulation of alluvium and was actively overgrown with forest vegetation. Radiocarbon (AMS) dates for this layer were obtained from the last 5 annual rings of the oldest buried trunk recovered from the section – 11967 ± 24 (SUERC-87226) – and from

Table. Information on wood samples

Sample location	Lab number	Material	Radiocarbon date ^{14}C (uncalibrated/bp)	Source
Sukhokit, stump horizon, soil 2	SUERC-87226	Wood of the first 3 annual rings, sample 4	12124 ± 25	Own data
Sukhokit, stump horizon, soil 2	SUERC-87227	Wood of the last 5 annual rings, sample 4	11967 ± 24	Own data
Sukhokit, soil 1	SUERC-87225	Wood from soil 1	10564 ± 24	Own data
Volcano Trakhitovy Udokan volcanic field, soil from under the lava flow	ГИН-4086	Charred soil	12050 ± 650	Stupak, 1987
Dry stump horizon, soil 2	BETA- 432243	Wood of annual rings, sample 1	11770 ± 40	Own data
Muya river Kobylin channel, soil 1	BETA- 453117	Wood of annual rings, sample 1	34880 ± 260	Own data
Muya river Kobylin channel, soil 1	BETA-453118	Wood of the last 5 annual rings, sample 1	41080 ± 500	Own data
Muya river Shchuchya channel	СОАН-3447	Wood from the stump horizon	27025 ± 320 л.н	Filippov A.A., 1997
Ust'-Karenga-XII, excavation site 3, united cultural horizon 7	TKA-19745	Organics from within ceramic fabric – 7th cultural horizon	11825 ± 45	Own data
Ust'-Karenga-XII, excavation site 3, united cultural horizon 7	TKA-19743	Organics from within ceramic fabric – 7th cultural horizon	12175 ± 40	Own data
Ust'-Karenga-XIV, excavation site 12, united cultural horizon 7	TKA-19744	Organics from within ceramic fabric – 7th cultural horizon	11870 ± 40	Own data

the first annual rings of the same trunk – 12124 ± 25 (SUERC-87227) (Fig. 4). The preservation of the wood suggests that the sediments were frozen prior to the dissection of the left side of the channel by the Muya River. The position in the section is 13 meters above the current edge of the Muya River. *Layer 7* a packet of parallel, thinly bedded loams and sands; gleyed, dark gray, with a bluish tint and fragments of plant remains in the form of twigs, stem fragments, debris. Sections with oblique bedding are recorded in the strata. Deposits of this type and dynamics of lamination are found at archaeological sites downstream along the Vitim, e.g. Bol'shoy Yakor I, Kovrizhka II and III. The thickness of the layer along the strike is variable from 1-2 m. *Layer 8* - rhythmically layered sands and loams with interlayers of pebbles. The sands are well washed and sorted, and the pebble interlayers are themselves interlayered with silt. Fragments of a bison skull (*Bison sp.*), and the teeth of a horse (*Equus caballus*) were found in a redeposited state at the base of the sediments near the water's edge. The thickness of the deposit is c.10 m. *Layer 9* - has a pebble-boulder base, a stone substrate of varying degrees of roundness and sizes from 1x0.7 m to 0.20x0.10 m. The stone substrate includes granites, limestones, igneous rocks, aggregates, infilled with coarse and medium-grained sands. The observed thickness of the low-water level in the Muya River is about 1 m along the strike of the section.

On the basis of the structure, it can be assumed that in the middle part of the section (along the strike) corresponds with an ancient channel of the Sukhokit stream, the ancient mouth of the stream. The channel is filled with large quantities of wood residues, both in the form of whole trunks and their fragments in a good state of preservation. The tree species include spruce, pine, larch, birch, and poplar. The fill is represented by sands and loams in a layered form. The total depth of the channel cut is 6 meters and its width along the strike of the section is more than 10 m. The channel cuts through the stump horizon and can be regarded as epigenetic in relation to the level of formation of the drained surface and its re-colonization by woody vegetation.

3.2. Dendochronological reconstructions from buried trees

For dendrochronological analysis, we took wood samples from the section of the Sukhokit stream and, for comparative analysis, from the much older section of the Kobylin channel. All samples were cross-dated, and 2 samples from Sukhokit. and one sample of the Kobylin channel were radiocarbon dated, which made it possible to obtain a relative time reference for these chronologies. In ten samples out of 23 obtained at Sukhokit, the date of death is the same, and dates back to -11950. The date of death of 4 samples is in the range between -11950 and -11945 years, however, they may lose the last rings due to poor preservation. Cross-dating of tree-ring series of samples of the Kobylin channel also showed a coincident date of death for four fossil tree samples. The consistent death of a large proportion of the trees found, given that the samples were collected *in situ*, confirms the catastrophic nature of the events (Fig. 4).

Fig.4. The level of the palaeolake of the Sukhokit stage (elevation 740 m above sea level) at the Param canyon and the Kilikanda valley spillway.

Tree-ring growth patterns, established on the basis of modern trees, show a reliable response to atmospheric moisture conditions and this enables a regional drought index to be established (Cook et al., 2010). In the growth ring dynamics of both the Sukhokit and Kobylin samples, several periods of depression are evident and typical for most samples (Fig. 5.) The average sensitivity index of the tree-ring series from Sukhokit is 0.31, which indicates the presence of a pronounced response to environmental conditions in the studied tree-ring series. It can be assumed that the periods of depression in the chronologies "Sukhokit" and "Kobylin channel" are closely related to droughts. However, while the average tree-ring width in the Sukhokit samples correlates with the tree-ring width of modern trees, the average tree-ring width in the Kobylin channel samples is significantly lower. The sensitivity index of the Kobylin samples is somewhat higher, calculated as 0.35, and the periods of depression are more pronounced.There is reason to believe that during the life of the trees found in the Kobylin channel, the environmental conditions differed significantly both from those during the life of the Sukhokit trees and from modern conditions (Table). Probably, the varation in radial growth in the samples of the Kobylin channel reflect a response to temperatures rather than precipitation, and chronological depressions are associated with periods of intense cold.

It is important to note that periods of growth supression have a periodicity.The tree-ring chronology "Sukhokit" contains a fairly stable 11-year cycle, corresponding to the cyclical nature of solar activity. The frequency of manifestations of periods of depression increases around the time of death of the trees and the catastrophic flooding of the basin.

3.3. Palaeoreconstruction of the dammed lake formation

In the Sukhokit section, a chain of successive geological events is recorded, which affected the vast territory of the Vitim plateau and the Baikal-Patom plateau. **The first event** (from bottom to top along the section) is the emergence of the terrace-like surface in the bottom of the Muya-Kuanda depression from the dynamic regime of formation due to periodic flooding. It is fixed by the 1st buried soil and tree trunks of various ages (from 89 to 48 years), which all died at the same time. **The second event** is the catastrophic flooding which not only filled the Muya-Kuanda basin, but also the valleys of the Vitim and its tributaries up to 500 km upstream. This is recorded by a layer of lacustrine alluvium that overlapped the larch forest that grew during the "dry period" of soil formation (the stump horizon itself). The depth of this lake was 110 m, and resulted in the deposition of a significant volume of lacustrine sediments not only at the site itself but across the ancient landscape, including those where ancient human settlements have since been found – e.g. at the mouths of the Karenga, Yumurchen, Oktorokon rivers. (Fig. 2). According to radiocarbon dating, the existence of this vast lake is between 11967 ± 24 (the date of death of the trees) and 10564 ± 24 (the time of the formation of the 2nd buried soil), that is, 1175 years. **The third event** is the catastrophic collapse of the lake, traces of which are recorded downstream along the Vitim in the form of extreme levels of erosion in the sections of the sides of the valley, the deposition of giant boulders on various forms of relief, the deposition of sandy strata both in the Vitim valley and in the valley of the river Lena (Peleduysky and Nyuysky sites). **The**

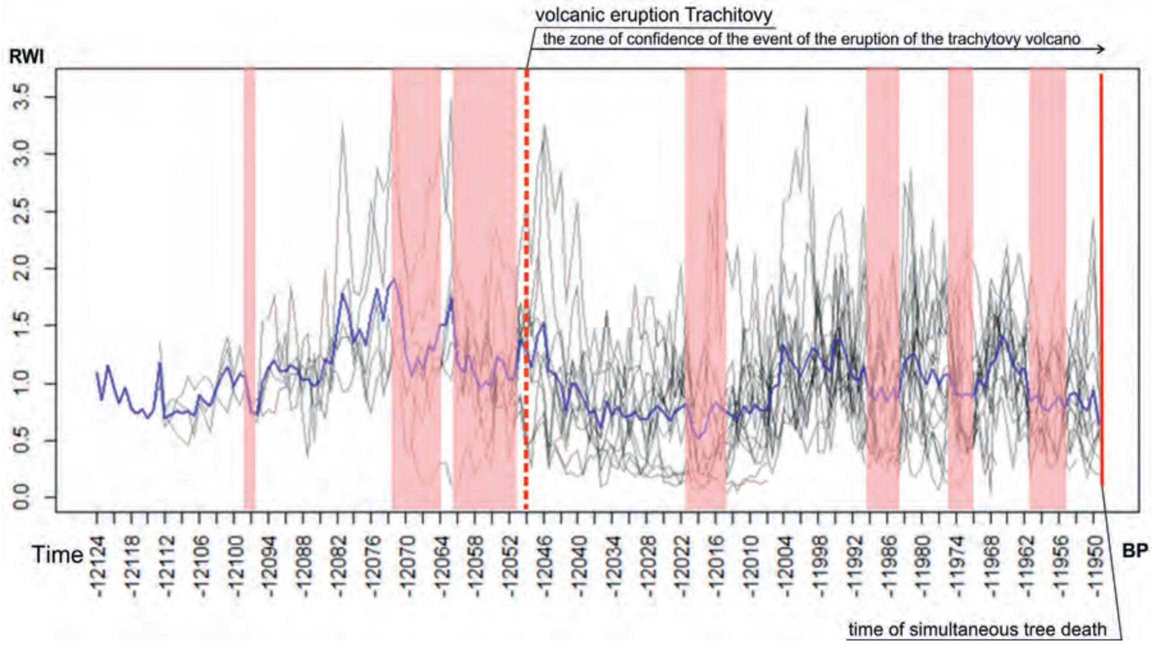

Fig.5. Individual tree-ring series (the average value is shown in blue, the characteristic periods of depression are highlighted in red).

fourth event is the drainage of the bottom of the Muya-Kuanda basin, which is recorded by the formation of the 2nd buried soil. The period of drainage of the bottom of the basin, judging by the thickness of the soil, was shorter than the period of formation of the 1st soil. After the formation of the 2nd buried soil, the humidity in the region suddenly increases again and this surface for the second time passes into the regime of rhythmic river alluvial accumulation with the deposition of sands and loams, which sealed the earlier deposits.

The section at the mouth of the Sukhokit is, perhaps, the only one in the Muya-Kuanda basin, where the time of the existence of this palaeolake can be dated so accurately and reliably. Based on this, the question arises: what reasons can explain such sudden, sometimes catastrophic, transformations of the Vitim and Baikal-Patom plateaus? What are the timelines for these geological events?

Floodplain stabilization, associated with the end of regular alluvial accumulation on the terrace of the Sukhokit stream before the formation of the palaeolake was accompanied by waterlogging and the formation of peaty soils (soil 1). The subsequent overgrowing of the bottom of the basin with forest was associated with a period of low water levels in the region's rivers, when the amplitude of annual floods was insignificant and the terrace-like surface at the mouth of the Sukhokit stream was not flooded. This is confirmed by the analysis of the structure of annual rings in the tree trunks of the stump horizon, which indicate their formation in a relatively dry cold season (Fig. 3A, 3B; Fig. 5). What time period this process took is not yet clear, but as a first approximation, we can estimate at least 200 years, which were required for the growth of the trees themselves, plus the preceding time for the formation of the peaty soil itself. After the collapse of the palaeolake, the terrace-like surface at the mouth of the Sukhokit was again drained and passed into a cycle of soil formation, which is later replaced by a second phase active floodplain accumulation (Fig. 2).

The first soil (soil 1), on which forest vegetation settled belongs to the type of floodplain soils in which the process of soil formation itself was incomplete. The soil itself consists of several thin humus interlayers of loam and peat, separated by thin layers of light sand. Soil of this type can be observed on today's low floodplain of the Muya River, which is also covered with forests (spruce, larch, birch, pine), but periodically warms up during summer floods, leaving on forest litter and grass growing on the low floodplain an interlayer of fine-grained sand and silt (Fig. 3). In the composition of thin humus interlayers, there is an abundance of branches of woody vegetation, seeds, and fragments of wood. As noted above, this circumstance indicates that the formation of the soil itself, on which the forest of the Sukhokit stump horizon grew, took place under conditions reminiscent of the formation of the low floodplain of the Muya River today, subject to periodic flooding. However, this period was not long-term and took no more than 100-200 years.

As noted above, three radiocarbon dates were obtained from the stump horizon using wood. The first AMS-date (sample No. 1-2017) from a tree trunk that lived for 68 years 11780 ± 40 (BETA-432243) bp. was obtained in the Miami laboratory (USA). For a more accurate adjustment of the AMS dating method itself and to create a chronological reference point for local tree-ring chronology (with reference to an absolute time scale), two more AMS were obtained from the trunk of a tree (No. 4-2018) that, judging by the annual rings, lived for 89 years. As noted above, this sample was dated in the laboratory of the University of Glasgow (UK) (Fig. 4), providing dates for the beginning of tree growth – 12124 ± 25 (SUERC-87227) bp – the end of growth, caused by simultaneous mass death of trees in the flooded forest – 11967 ± 24 (SUERC-87226) bp (Fig.5). This operation served as a pleasing confirmation of the accuracy of the AMS dating technique. Taking into account the corrections to the dating, the age of the tree at the end and start dates is 107 years, which is an almost ideal definition of the real age, calculated by the annual rings, equal to 89 years! It should be noted that in the future there is the possibility to link this floating section of tree chronology to a continuous regional tree-ring chronology, and thereby achieve calendar accuracy of geological events. In the process, it is necessary to clarify that when comparing radiocarbon dates from different sections of the Vitim, we used only the results obtained by the AMS dating method. This refinement is essential, especially for determining the course of geological events of short duration, since from our own research we established and documented a significant difference between radiocarbon dating obtained by scintillation and AMS methods. In our case, this difference is calculated in 660 – 740 years. Evidently, this is of fundamental importance.

In ten samples of buried trees out of 23 excavated from the Sukhokit horizon, the date of death of trees coincides, and is determined by the boundary of 11967 ± 24 bp. Noteworthy is the fact that the dating of the palaeomagnetic excursions “Gothenburg” (12350 - 12400) and “Lashamp-Kargopolovo” (41000 bp) coincide with the dating of the palaeolakes of both the Sukhokit and Kobylin stages (Mörner, 1977; Krivonogov, 2001; Guskova et al., 2012; Nowaczyk et al., 2012). It is possible that the reason for the lower water levels in the Muya and Vitim, which resulted in a sudden end to the rhythmic process of the alluvial accumulation on the floodplain should be sought in these geomagnetic phenomena; in this case, “Gothenburg”, which – judging by radiocarbon dating – immediately preceded the growth of forest vegetation on the floodplain. It is also possible that the evolution of the position of the Earth’s core and associated geomagnetic changes caused increased volcanic activity in the region. This may be confirmed by dating of a soil (12050 ± 650 [GIN-4086]) which formed before the Trakhitovy eruption and was buried beneath the lava flow of the volcano on the Udokan volcanic plateau (Fig. 1) (Stupak, 1987). Some discrepancy between this dating and the date of the death of trees as a result of flooding on Sukhokit should be expected here, due to differences in the dating methodology and the specific character of the dated organic matter in each case. The date of the volcanic eruption was measured by the scintillation method, while the others used in the article use the AMS method. These methods vary considerably in the precision of measurement.

It is also worth noting, in this context, that Trakhitovy Volcano is located in close proximity, just 40 km, from the Param canyon section of the Vitim valley, where a water-retaining dam could have formed (Fig. 1; Fig. 4) (Stupak and Stupak, 1987; Kulchitsky et al., 1997). The formation of the dams for these palaeolake lakes is explained by different researchers in different ways: some adhere to the view that tectonic movements were involved, leading to the collapse of the Vitim valley in the Param canyon and the blocking of the channel (Kulchitsky A.A., Ufimtsev, Skovitina), many others see glacial action as the explanation for the formation of a retaining dam, a glacier presumably descending along the valley of what is now Lake Oron (Endrikhinsky et al., 1983; Filippov, 1997; Enikeev, 2009; Margold et al., 2018). In this context

In determining the position of the shoreline and, therefore, the maximum extent and volume of the palaeolake, the section of the Vitim valley at the outflow of the Muya-Kuanda basin is of central importance. This was noted from the first by researchers of Lake Muya, S.S. Osadchiy and A.A. Kulchitsky, who described a “breakthrough valley” in this area, which served as the outflow for part of the contents of the ancient lake, bypassing the retaining dam within the Vitim channel itself (Endrikhinsky et al., 1983; Kulchitskiy et al., 1997).

On the right side of the Vitim valley, at an absolute elevation of 740 m, is preserved a section of side valley (spillway) through which the waters from the dammed lake were carried (Fig. 1; Fig. 4). The total length of this valley is 4,900 – 5,000 meters with a maximum width of 750 meters and a depth of 180 meters. Lake Kilikanda, which now occupies the thalweg of a fragment of this ancient channel, and from which the valley gets its modern name. This lake reaches a depth of more than 12 m and contains practically no loose sediments of riverine origin: silts, sands, pebbles. In the bottom sediments of the lake, from a depth of about 8 meters, a 50-cm core was taken using an UWITEC unit. In general, the undisturbed sediments presented in this core, in thickness and material composition correspond to the Holocene sediments of similar lakes of the Baikal rift zone.

In its current condition, the Kilikanda discharge valley is an area with steep rocky sides and a bottom lined with remains of past rockslides. In the middle part of the valley on the right side, at an elevation of 860 meters, there is a fragment of pebbles from an older stage, when the valley had again served as a spillway. In the profile of the valley, on the right side, yet another rudiment is recorded, fixing earlier stage in the development of the valley, the shoulders of which are 37 meters above the bottom of the main valley (Fig. 1; Fig. 4). In this rudiment of an older valley, a small swamp-lake has also been preserved, though it has now passed into the stage of overgrowth.

In the opinion of the first researchers of palaeolakes in this region, all these indications show that the bed of the Kilikanda valley formed under the influence of repeated phases of extreme erosion resulting from the release of water from these dammed lakes, gradually deepening the valley, the last stage of which occurred with the formation of the dammed lake that flooded the forests of the Muya basin around 11967 bp (Endrikhinsky et al., 1983). Downstream, immediately behind Lake Kilikanda, the arched ridges of “giant ripples”, formed by flows of discharged waters are clearly visible along the left side of the valley. These formations are composed of pebble-boulder deposits with sand-grit filler reaching a width of up to 40 meters at the base. The difference in height caused by this last stage of erosion is 263 m along the 4500 m of the valley (Fig. 4).

In general, the dimensions of the Kilikanda valley correspond to the parameters of the modern Vitim channel in the Param canyon. The total length of the bypassed section of the Vitim valley, and hence the section occupied by the dam, is 11.4 km (Fig. 4). Judging by its position, could have arisen only under the conditions of the formation of a backwater in the Param canyon at the point where the Vitim leaves the Muya-Kuanda basin (Fig. 4). On this section of terrain there are no glacial landforms to point to a glacial origin of the retaining dam. The boundaries of the final forms of mountain-valley glaciers in the Baikal Upland were fixed by us at higher elevations located tens of kilometers from the Vitim valley (Ineshin, 2003). As noted above, several authors (Ufimtsev et al., 1997) have noted a probable tectonic origin for the retaining dam. Their arguments are based on the morphology of the slopes of the Vitim valley in this section of its valley and they propose a staged model of subsidence to explain the process. The remnants of these subsidence stages are traced along the left side of the Vitim valley in the Param canyon (Fig. 4). Unfortunately, the presence of a spill way in the Param Canyon was not considered by the researchers who put a glacial explanation for the origin of the palaeolake lake in the Muya-Kuanda Basin. Instead, they described a spill way downstream of the mouth of Lake Oron that redistributed part of the Vitim discharge bypassing the retaining dam in the Delunoron narrowing 116 km downstream of the Param narrowing (Margold et al., 2018).

3.3. The connection between the palaeolake and archaeological sites

Whatever its cause, the dammed lake occupied a vast territory, including not only the Muya-Kuanda basin, but also the Vitim valley and its tributaries upstream (Fig. 2). Understanding fully the impact of these catastrophic events on the human populations of the basin is still in its early stages, but it seems to be very direct. Lacustrine-type alluvial deposits are well documented at the multi-layered archaeological complex at the mouth of the Karenga River, the right largest tributary of the Vitim. One of the most extensively studied archaeological complexes in the region, the Ust'-Karenga complex is located 400 km upstream from the Muya-Kuanda Basin (Fig. 6) and consists of 15 multilayer sites, which were defined and excavated over a period of more than twenty years, beginning in 1975. The cultural remains of the lower horizons (7, 8, 8A) were deposited under the conditions of the formation of river alluvium but were overlain by an almost 1.4 m thick layer of thinly bedded sterile sands with slightly different bedding dynamics to those below (Fig. 2A). Until recently, it was believed that the origin of this part of the deposit was also riverine. However, as the cultural remains are reliably dated by the radiocarbon method based on both charcoal from hearth deposits and organic matter in the fabric of ceramic vessels – it is possible to precisely compare and correlate the chronological position of the cultural remains and the dating of the remains from the Sukhokit section. The coincidence is striking: the dating of the 7th cultural horizon, which contains the oldest record of ceramic vessel production to the west of the Pacific watershed, immediately precedes both the accumulation of the thinly bedded sands and the formation of the palaeolake attested in the Sukhokit section (Table; Fig. 2A). It is true that the situation is complicated and the AMS dating of the cultural remains using organic matter from the ceramic fabric obtained by the AMS method at the archaeological complex itself indicates a certain variation in date between individual local points within the complex itself and the presence of cultural remains of different dates at the same point (Vetrov and Ineshin, 2019). However, in general

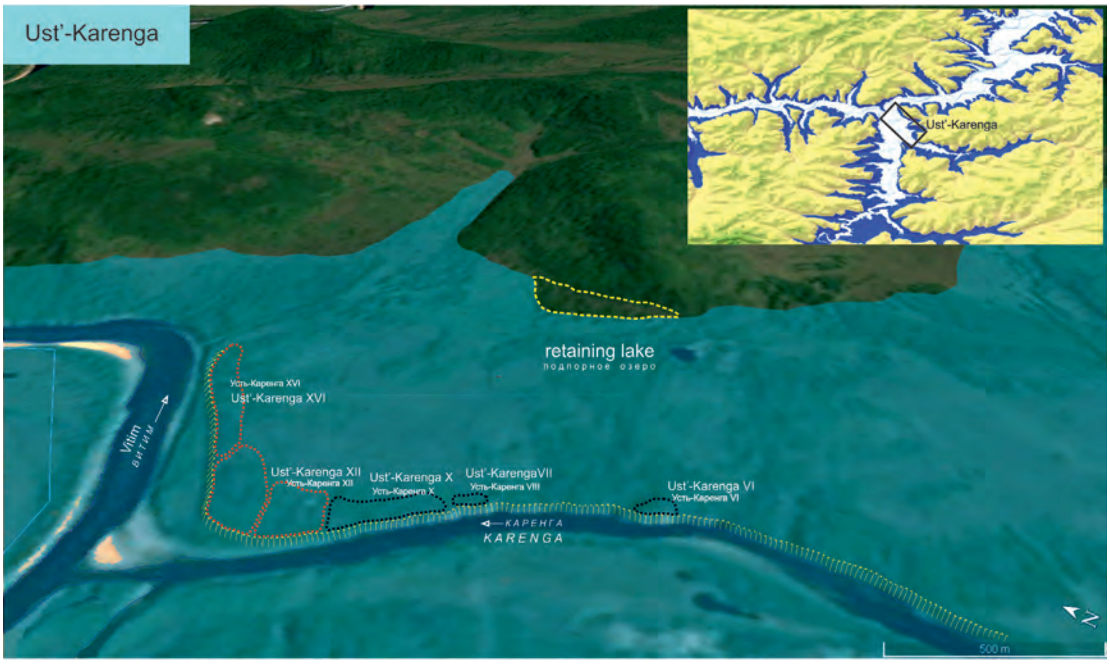

Fig.6. The level of the palaeolake of the Sukhokit stage (elevation 740 m above sea level) at the mouth of the Karenga River and archaeological sites buried by lacustrine sediments.

terms, we can say that the sites of the Ust'-Karenga archaeological complex were formed about 50-370 years earlier than catastrophic flooding associated with the formation of the palaeolake, which would have covered this section of the Vitim basin with between 23 and 63 metres of water (Fig. 2; Fig. 6). Such a catastrophic geological event must have had a dramatic effect on cultural practices and adaptation mechanisms. Indirect signs of this impact upon the ancient inhabitants of the Vitim basin have been recorded and are the subject of separate article (Vetrov and Ineshin, 2019).

Another interesting fact is the overlap of the features of these conditions of alluvium accumulation, which preceded the formation of soil and the features of the conditions of alluvium accumulation at the archaeological site Bol'shoy Yakor I, which is located 550 kilometres downstream of the Vitim (Fig. 1C) (Ineshin and Tetenkin, 2010). There, in the section of the terrace at an elevation of 14 metres, river alluvium was formed under the action of the same mechanisms, with the same periodicity and at the same time as those seen in the middle part of the Sukhokit section. The main feature revealed in the 3.5-meter strata of the floodplain alluvium of the Bolshoi Yakor is the fact that the sediments that buried the cultural remains of temporary seasonal hunting camps in the chronological range from 14,000 to 12,000 bp were deposited under conditions of a reduced flow of the Vitim River (Fig. 1).

4. Conclusions

Thus, as a result of the data obtained during the study of the palaeolake of the Muya-Kuanda basin, it was possible to clarify the time of formation and the duration of the existence of the dammed palaeolake of the Sukhokit stage. As research develops further in this direction, it will be possible to link these geological events more closely to a dendrochronological scale and thereby to obtain absolute calendar chronology for these catastrophic geological processes. Synchronization of the dating of this event with data on the eruption of nearby volcanoes, makes it possible, with a high degree of probability, to confirm the hypothesis put forward by A.A. Kulchitsky and G.F. Ufimtsev regarding the tectonic origin of the retaining dam that blocked Vitim and its location (Kulchitsky et al., 1997). Further research will allow us to clarify this relationship with new dates on organic material associated with this volcanism. However, annual rings in the trunks of larch trees from the Sukhokit stump horizon indirectly testify in favor of a tectonic rather than the glacial origin for the retaining dam. The cold dry climate reflected in the annual rings do not indicate conditions in which we might expect the formation of significant masses of ice across the North Muya ridge. Further study of buried wood in the Muya-Kuanda basin will allow us to compile high resolution palaeoclimatic models with the possibility to explore real cause-and-effect models for the relationships between natural events and the activities and traditions of the ancient populations of the Vitim basin. Already, the results obtained made it possible to synchronize aspects of the settlement of the Vitim valley and the catastrophic events associated with the emergence of the Sukhokit stage palaeolake (11967-10564 bp). Undoubtedly, these apparently catastrophic events played a significant role in the preservation of the remains of human activity. The burial of these sites in 1.4m of sterile lacustrine alluvium enabled us to obtain clear *in situ* evidence for one of the oldest ceramic industries in Northern Eurasia (11870 - 12175 bp) (Fig. 2). The formation of overlapping cultural remains of sands near the conditions of a backwater lake is also confirmed by data on diatoms and pollen from the section. The climatic conditions, reflected in the graph of the growth of annual rings in wood from the stump horizon, directly reflect with a high degree of detail the living conditions of the ancient population at the sites of the Ust'-Karenga archaeological complex and Bol'shoy Yakor I downstream of the Vitim. If we consider that ceramic production must have been an important adaptive strategy for these communities living in the harsh conditions of North Asia (conditions directly attested in the tree ring data) we can assume that the survival of human communities was possible thanks to the careful management of food resources. Movements of groups of the ancient population from sites at the mouth of the river. Karenga to the areas of the lower reaches of the Vitim is attested by observations and analyzes on the movement of exotic rocks of stone raw materials, which allows us to consider the oldest layers of the Ust'-Karenga complex as the remains of the base sites of ancient hunter-fisher-gatherers, who developed a unique model of economic activity for the development of mountain landscapes of the Vitim plateau (Ineshin and Tetenkin, 2010).

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Conflict of interests

Authors declare no conflict of interests.

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