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Polychlorinated biphenyls in the tributaries of Southern Baikal

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ABSTRACT. In the aquatic ecosystem of Lake Baikal, global atmospheric transport is regarded as the dominant source of polychlorinated biphenyls (PCBs). Relatively high level of PCB concentration in the southern basin of the lake is associated with PCB influx from local sources. The waters of the tributaries of Southern Baikal, which have watershed basins on the slopes of the Khamar-Daban ridge, possess significant potential as a source of pollutants. The article presents the results of PCBs monitoring in the waters of the rivers Utulik, Solzan, Khara-Murin, Snezhnaya, and Pereemnaya in 2017 and 2019. PCB concentrations in the waters of the tributaries were estimated by the total concentration of seven indicator congeners Nos. 28, 52, 101, 118, 138, 153, and 180 (ΣPCB_7) in water samples taken at the estuaries of the rivers. The ΣPCB_7 level in the waters - from 0.02 to 1.5 ng/L, can be comparable to or exceed that in the littoral zone of the lake. An assessment of the removal of PCBs to the southern part of Lake Baikal indicates a minimal influx of pollutants of this class with tributary waters. In 2017, the number of PCB indicator congeners that entered Lake Baikal with water runoff was estimated to be between 1.7 and 3.1 g in May and between 7.7 and 26 g in September. In extreme conditions, the water runoff of PCBs can reach 40-170 g per month, like in September 2019.

Keywords: PCB, waters of tributaries, Lake Baikal

1. Introduction

Surface water pollution by persistent organic pollutants (POPs) is one of the most important problems in the world community. The control system of POPs in the water of Lake Baikal, a source of world-class drinking water, pays a special attention to polychlorinated biphenyls (PCBs), because this class of organic pollutants is highly toxic and stable and has the maximum accumulation in biota (Kucklik et al., 1994; Nakata et al., 1995; Samsonov et al., 2017).

Taking into account the widespread use of PCB in electrical equipment of distribution stations, the extent of energy development and the volume of electricity consumption in East Siberia, the influx of PCB to the environment poses the greatest danger to wildlife and human health. The contribution of coplanar (dioxin-like) PCBs to the total toxicity equivalence of dibenzodioxins, dibenzofurans and PCBs (TEQ_{1998}) in commercial fish exceeds 70% (Mamontov et al., 2000), and in examined people from the Baikal region – 50% (Shelepchikov et al., 2012).

When PCB was monitored in the Baikal water in 1991-1992 (Iwata et al., 1995; Kucklick et al., 1996), there was a trend toward an increase in the total concentration of congeners (ΣPCB) in the upper water layer from the northern to the southern basins of the lake. This trend was associated with the influx of pollutants from local sources to the southern part of Lake Baikal. At the present stage, the assessment of PCB concentration in the Baikal water was carried out by Research and Production Association "Taifun" in 2014 and Limnological Institute SB RAS in 2015 (Gorshkov et al., 2017; Samsonov et al., 2017). Independent studies recorded an increase in ΣPCB in the Baikal water: the maximum ΣPCB concentration became 3.5 times higher, and the minimum concentration – up to 70 times higher. These studies also revealed maintaining a higher PCB pollution level of the water in the southern basin of the lake (up to two times compared to the northern part of the lake, Gorshkov et al., 2018).

The presence of ΣPCB in the atmospheric air of the southern part of Lake Baikal (the 2013-2014 monitoring; weather stations in the Listvyanka, Kultuk and Tankhoy settlements) had a wide range of concentrations, from 7 to 900 pg/m^3, and the share of POPs transported in the form of aerosols was 8-12% of the total amount of substances concentrated from the atmosphere. In particular, at the Tankhoy and Kultuk stations, there were several maximums of ΣPCB concentrations in the

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atmospheric air during the observed season, which were from 3 to 20 times higher than the maximums at the Listvyanka station. The recorded changes in PCB concentrations were explained by the influx of pollutants from local sources to the coast (Samsonov et al., 2017). It should be noted that the PCB content in the soils of Southern Baikal corresponds to the level of soil pollution in the industrially developed areas of northern Europe and is almost five times higher than in areas of Northern Baikal (Mamontov et al., 2018).

The tributaries of Southern Baikal are a high-potential source of pollutants in its ecosystem. These tribitaries have large areas of watershed basins on the slopes of the Khamar-Daban ridge, from 60 to 3000 km^3, where a great volume of atmospheric precipitation with high POP concentrations falls due to the transport of the polluted air masses from the industrial zone of the Baikal region and emissions from the sources on the coast (Kokorin and Politov, 1991). Can river runoff be a source of PCBs found in the waters of Lake Baikal, and what is its contribution to lake water pollution? To answer this question, in 2017 and 2019 PCBs were monitored in the waters of the tributaries of Southern Baikal, with water sampling at the estuaries of the rivers, in the littoral and in pelagic zones of the lake along the corresponding sections. PCB concentrations in water samples were estimated by the total concentration of seven indicator congeners, Nos. 28, 52, 101, 118, 138, 153, and 180 (Σ_7PCB).

2. Materials and methods

Water samples from the tributaries, the littoral zone and pelagic zone of Southern Baikal were taken in May and September of 2017 and 2019 (Fig. 1). Wastewater from the treatment facilities of the town of Severobaikalsk and in the Tyya River was sampled in February 2020. At each station, we took two samples in 1 L glass bottles, which were covered with a lid having a pad of aluminium foil. Then, 0.5 cm^3 of a sodium azide 1 M aqueous solution (High Purity Grade; Merk) was added, and the samples were stored at +5 °C in the laboratory until analysis. Indicator PCBs in water samples were determined according to the procedure (FR.1.31.2020.36324). This procedure included the stages of liquid-liquid PCB extraction with *n*-hexane, the concentration of extracts to a volume of 0.1 ml and analysis of concentrates by GC-MS/MS on an Agilent Technologies 7890B GC System 7000C GC/MS Triple Quad gas chromatograph with an HT8 capillary column (30 m x 0.25 mm x 0.25 μm). Quantification was carried out according to the method of internal standards using the $^{13}C_{12}$-PCB mixtures (Nos. 28, 52, 101, 118, 138, 153, and 180; Marker-7 PCB Mixture (W/PCB-118)) as surrogate internal standards having a concentration of each congener equal to 0.11 ng/mL with a relative error (±δ, P=0.95) of 35%.

The *n*-hexane for chromatography produced by NPK KRIOCHROM LLS (grade 1) which was distilled before analysis, was used for extraction. The purity of the solvents, laboratory ware and chromatographic system was evaluated by conducting blank experiments.

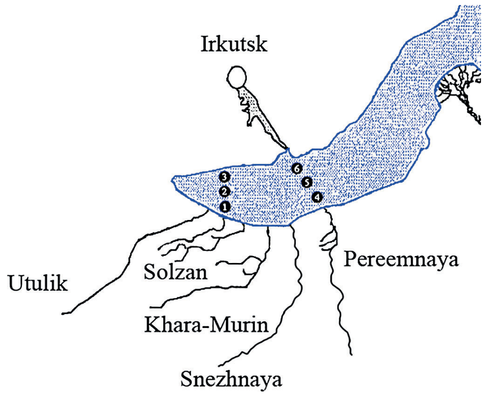

Fig. 1. Scheme of the PCB monitoring site in South Baikal. Sampling at river estuary and in the pelagic zone of a lake, station ●: – 1 – 3 km from the estuary of the Solzan River; 2 - the Solzan-Marituy section, centre; 3 – 3 km from the Marituy settlement; 4 - 3 km from the Tankhoy settlement; 5 - the Nankhoy-Listvyanka section, centre; 6 - 3 km from the L.istvyanka settlement.

3. Results and discussion

In 2017 and 2019, monitoring PCBs in the rivers Utulik, Solzan, Khara-Murin, Snezhnaya, and Pereemnaya revealed high seasonal and interannual variability of Σ_7PCB concentrations (Fig. 2). PCBs were present in the range of Σ_7PCB concentrations from 0.02 to 1.5 ng/L (average value 0.34 ng/L, median 0.20 ng/L). In the spring of 2017, Σ_7PCB concentrations corresponded to the minimum level close to the detection limit of indicator congeners, from 0.02 to 0.09 ng/L. Repeated monitoring in September indicated that PCB concentration in the waters of tributaries became two-five times higher, and in the Snezhnaya River – ten times higher. Σ_7PCB concentrations detected in May 2019 were comparable with the results of monitoring conducted in September 2017. However, in the autumn of 2019, we recorded an increase in PCB concentrations. In the rivers Solzan, Khara-Murin and Snezhnaya, Σ_7PCB concentrations were 3-8 times higher than they were in May 2019, and 10-70 times higher than they were recorded in May 2017.

Σ_7PCB concentrations at the estuaries of the rivers could be comparable to or exceed the concentrations in the littoral zone of the lake, for example, in the spring in the Pereemnaya River and along the Tankhoy-Listvyanka section (Fig. 3) as well as in September in the Solzan River and along the Solzan-Marituy section (Fig. 4). Estimation of the influx of PCB to the water of Southern Baikal basin indicates a wide range of masses of this pollutant, which enter the lake with the waters of the tributaries. For instance, in May and September 2017, the amount of Σ_7PCB, which entered with water runoff, was minimum, from 1.7 to 3.1 g and from 7.7 to 26 g, respectively, with the maximum PCB removal with the water from the Snezhnaya River, which has the largest area of watershed basin (3000 km^2) (Table).

In the atmosphere and water, PCBs are associated with aerosol particles or suspended matter, which are mainly deposited on the earth's surface near the sources or move to the bottom sediments of water bodies. Therefore, PCBs that enter the aquatic ecosystem through the atmospheric channel of from the watershed basin of rivers are identified as fractions of light low-molecular weight PCB congeners having higher volatility and lower hydrophobicity. Owing to these crucial features, mainly tri-, tetra- and penta-chlorinated biphenyls represent the composition of PCB in the water.

The number of PCB congeners detected in the Baikal water reaches 34 compounds; their total concentrations range from 1.4 to 7.2 ng/L. Profiles of the homologous groups of PCBs that present in the pelagic zone of the lake are similar and show the dominance of tri-, tetra and penta-chlorinated biphenyls. This homologous ratio indicated the distant atmospheric transport as the main source of PCBs in the aquatic ecosystem. Heavy congeners with a high degree of chlorination detected in the water are due to the influx of PCBs to the water body from local sources (Iwata et al., 1995; Kucklick et al., 1996; Gorshkov et al., 2017; Samsonov et al., 2017).

Indicator congeners (Nos. 28, 52, 101, 118, 138, 153, and 180) are characterized by a maximum content in the homologous groups of PCBs; their ratio reflects the profile of PCBs present in the studied water object. With a decrease in PCB concentration, the number of congeners available for the quantitation within the standardized control frameworks also decreases. The preservation of a number of controlled congeners requires an increase in the volume of samples, higher sensitivity and reliability of the method at the final stage of determination procedure. Control of PCB in the water object based on the determination of indicator congeners establishes a strict framework for assessing monitoring results, taking into account the constant qualitative composition of the fraction of determined congeners.

In the waters of the Baikal tributaries, we detected seven indicator congeners with the maximum concentrations of tri-, tetra and penta-chlorinated PCBs (Nos. 28, 52, 101, and 118). In samples with minimum PCB concentration in water, at the level of the detection limit of individual congeners equal to 0.01 ng/L, we identified only two-four congeners (monitoring results of May 2017, Fig. 2). At an increase in the PCB content in the water of the tributaries to the level of Σ_7PCB equal to 0.2-0.4 ng/L (September 2017, May 2019) there are six compounds in the indicator PCB fraction. Congener No. 180, which contains seven chlorine atoms in the structure, was detected in samples with a relatively high Σ_7PCB content, from 0.85 to 1.5 ng/L (Fig. 2, September 2019). In the indicated season, increased concentrations of Σ_7PCB were detected both in the pelagic zone of the lake at the stations Nos 4 and 5, as well as at the estuary of the Solzan, Khara-Murin and Snezhnaya rivers (Fig. 2, Fig. 3). The analysis of the latter water samples revealed significant scatter in the results of analyte determination: up to seven times. This phenomenon of the composition of the samples might be due to high heterogeneity of the PCB distribution in the river water flow, which occurs when pollutants come from the watershed area.

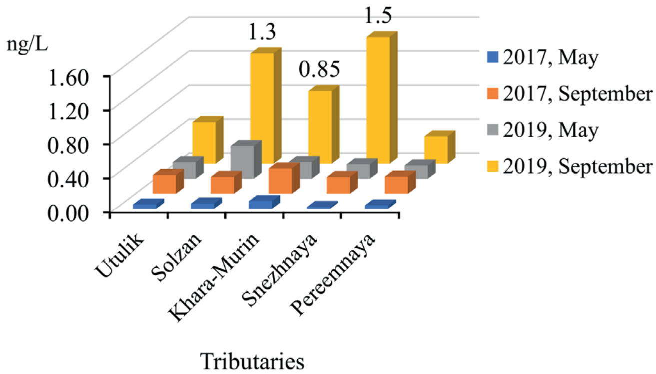

Fig. 2. Σ_7PCB concentrations in the tributaries of Southern Baikal.

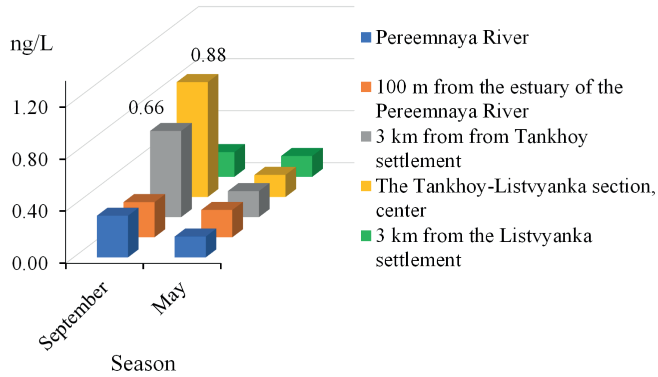

Fig. 3. Σ_7PCB concentration at the estuary of the Pereyemnaya River, in the coastal zone and the upper water layer of the Tankhoy-Listvyanka section. Water sampling in May and September 2019.

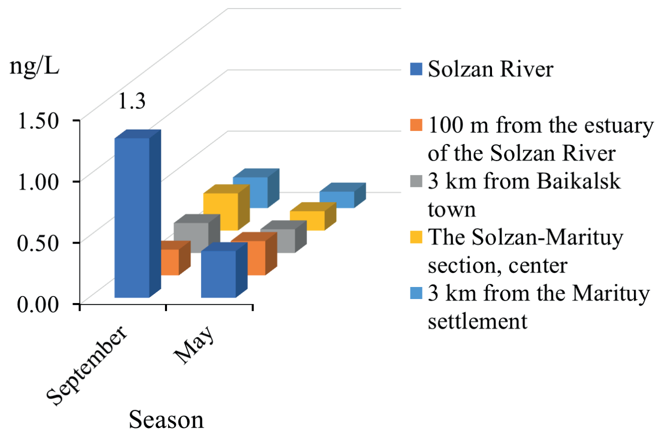

Fig. 4. Σ_7PCB concentration at the estuary of the Solzan River, in the coastal zone and the upper water layer of the Solzan-Marituy section. Water sampling in May and September 2019.

When Σ_7PCB concentrations and volume of water runoff are at levels of 0.85-1.5 ng/L (Fig. 2) and 0.05-0.13 km^3 (Table), respectively, the amount of PCB removal under such conditions can reach 40-190 g per month. PCB influx in such amount is probably associated with the extreme events: global wildfires in East Siberia in 2019 and release of POPs on the slopes of the Khamar-Daban ridge from the atmosphere. The presence of organochlorine pollutants in smokes of wildfires results from their desorption from the vegetation, in which they accumulated during the life cycle when they came from the atmosphere and soil.

Table. Estimation of the influx of polychlorinated biphenyls (Σ_7PCB) in Lake Baikal with the tributaries of Southern Baikal

Tributaries	Area of watershed basin, km^2	Average height of the basin, m, absolute level	Sampling period					
			May, 2017			September, 2017		
			Σ_7PCB, ng/L	volume of water runoff*, km^3	Σ_7PCB influx, g	Σ_7ПХБ, ng/L	volume of water runoff*, km^3	Σ_7PCB influx, g
the Utulik River	960	1140	0.06	0.028	1.7	0.22	0.035	7.7
the Khara-Murin River	1130	1520	0.08	0.063	5.0	0.30	0.048	14
the Snezhnaya River	3000	1420	0.02	0.054	3.1	0.20	0.130	26
Pelagic zone **	-	-	1.1	-	-	0.40	-	-

Note: * - Data from the Russian Hydrometeorological Service (Roshydromet); ** - average value for the upper water layer (5-200 m) in the centre of the Tankhoy-Listvyanka section.

In the context of assessing the influx of PCBs in such amount of interest are the results of determining PCBs in wastewater. PCB content in wastewater discharged into Lake Baikal after passing treatment facilities showed a high content of pollutants of this class. PCB concentration was estimated by the total concentration of the detected congeners equal to 35 ng/L (32-24 congeners) as well as Σ_7PCB concentration equal to 10 ng/L. At a distance from the sewage discharge collector of up to 2.5 km, ΣPCB and Σ_7PCB concentrations in the Tyya River were 35 times lower, up to a level of 0.95 and 0.31 ng/L, respectively. It should be noted that a decrease in the concentration of PCBs was due to a decrease in the proportion of “light” congeners, and the composition of the PCB fraction corresponded to the PCB content in the tributaries and the upper water layer of the Baikal pelagic zone (Fig 5).

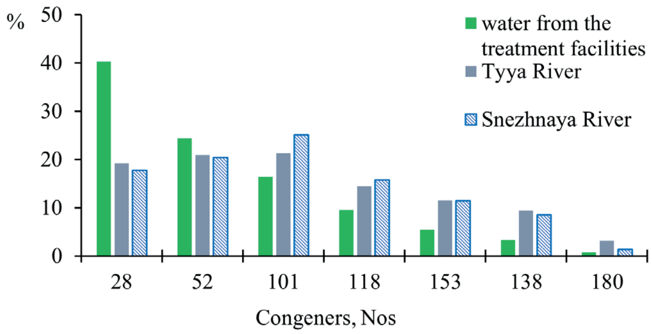

Fig. 5. The proportion of indicator congener PCBs in Σ_7PCB, %:

in wastewater after passing treatment plants in Severobaikalsk, Σ_7PCB 10 ng/L;

in surface water in the river Tyya, 2.5 km from the sewage discharge collector, Σ_7PCB 0.31 ng/L;

in water at the estuary of the Snezhnaya River, Σ_7PCB 1.5 ng/L.

4. Conclusions

The waters of the tributaries of Southern Baikal have high seasonal and interannual variability in Σ_7PCB concentrations, ranging from 0.02 to 1.5 ng/L, with the dominance of tri-, tetra- and pentachlorinated congeners in the composition. The level of Σ_7PCB in the waters of the tributaries can be comparable to or exceed that in the littoral zone of the lake. Assessment of the removal of PCB to the southern part of Lake Baikal with the waters of the tributaries indicates the possible influx of this pollutant to the lake in a wide range of masses, up to two orders of magnitude. According to the monitoring data, masses of PCB indicator congeners that came with water runoff in May and September 2017 correspond to the ranges from 1.7 to 3.1 g and from 7.7 to 26 g. In extreme conditions, the water runoff of PCBs can reach 40-190 g per month, like in September 2019.

Acknowledgements

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Original Article

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Phylogeny of the freshwater lineages within the phyla Actinobacteria (Overview)

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ABSTRACT. This review presents molecular classification of freshwater Actinobacteria based on the phylogeny of the 16S rRNA gene. We show the classification of the entire phylum Actinobacteria and the taxonomic rank of freshwater lineages of Actinobacteria within this phylum. The discovery history of different groups of freshwater Actinobacteria is considered. We have systematized the information about the phylogeny of cultivated and uncultivated freshwater Actinobacteria and give their brief description. Data is provided on freshwater groups of Actinobacteria found in different ecotopes of Lake Baikal.

Keywords: 16S rRNA gene-based phylogeny, phylum Actinobacteria, freshwater lineages of Actinobacteria, Lake Baikal

1. Introduction

Phylum Actinobacteria is one of the largest taxonomic units in the domain Bacteria. It consists of gram-positive bacteria with a high G+C DNA content (from 51 to 70%) (Ventura et al., 2007). Actinobacteria have a diverse morphology, from coccoid (*Micrococcus spp.*), rod-coccoid (*Arthrobacter spp.*) forms to fragmenting hyphae (*Nocardia spp.*) and highly differentiated branched mycelium (*Streptomyces spp.*). This phylum is widespread, especially in soil, and it includes saprophytes (inhabitants of soil, vegetation, the gastrointestinal tract of animals and humans), symbionts and pathogens (Ventura et al., 2007). Actinobacteria are biotechnologically important producers of various biologically active substances that are widely used in industry, medicine and agriculture (Barka et al., 2016).

It has been long believed that actinobacteria isolated from water are of soil origin, and they do not develop in the aquatic environment, having inactive state in the form of spores (Goodfellow and Williams, 1983). The molecular methods independent of cultivation, mainly such as fluorescent cell labelling and PCR analysis of 16S rRNA gene sequences, revealed that uncultivated members of Actinobacteria are numerous and cosmopolitan inhabitants of freshwater ecosystems, constituting the dominant fraction of heterotrophic bacterioplankton (Glöckner et al., 2000; Zwart et al., 2002; Warnecke et al., 2004; Allgaier and Grossart, 2006; Newton et al., 2011). After evidence of the fundamental difference of freshwater bacterioplankton from soil and marine bacteria has accumulated, Actinobacteria are under the scrutiny of researchers as one of the main groups of the freshwater bacterial community (Methe´ et al., 1998; Rappe´ et al., 1999; Glöckner et al., 2000; Zwart et al., 2002).

This overview aimed to systematize the taxonomic data on uncultivated and cultivated freshwater Actinobacteria obtained from the phylogeny of the 16S rRNA gene.

2.1. Molecular classification of the phylum Actinobacteria

The phylogeny of the 16S rRNA gene divides Actinobacteria into six classes, such as Actinobacteria, Acidimicrobiia, Coriobacteriia, Nitriliruptoria, Rubrobacteria, and Thermoleophilia (Ludwig et al., 2012). According to this classification, the largest class Actinobacteria includes 15 orders, and other classes consist of one-two orders.

In the phylogenetic tree, there are two large clades within the class Actinobacteria. The first clade includes the orders Actinopolysporales, Corynebacteriales, Glycomycetales, Jiangellales, Micromonosporales, Propionibacteriales, and Pseudonocardiales. The second clade includes the orders Actinomycetales, Bifidobacteriales, Kineosporiales, and Micrococcales. The orders Catenulisporales, Streptomycetales, Streptosporangiales, and Frankiales are distinct genetically separated branches within the class Actinobacteria (Ludwig et al., 2012). Analysis of 100 whole-genome sequences of the main families and orders belonging to the class Actinobacteria divided the

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order Frankiales into four monophyletic orders, such as Frankiales, Geodermatophilales, Acidothermales, and Nakamurellales (Sen et al., 2014). The order Micrococcales is also polyphyletic and requires additional revision, but officially this cannot be done due to the insufficient number of whole genomes. Thus, at present, the class Actinobacteria includes 18 recovered orders.

2.2. Discovery of freshwater Actinobacteria

Uncultivated freshwater Actinobacteria were first discovered in 1997 in the Adirondack Mountain Lakes of the USA (Hiorns et al., 1997). In the phylogenetic tree, they formed an ACK-4 cluster that is separate from other known cultivated actinobacteria. This group of Actinobacteria called hgcI was detected in great numbers in lakes Fuchskuhle (Germany) and Gossenkollesee (Austria) as well as in Lake Baikal (Russia) (Glöckner et al., 2000).

Zwart et al. (2002) showed that freshwater Actinobacteria are autochthonous and cosmopolitan, and he identified five proposed clusters typical of freshwater uncultivated Actinobacteria, which were combined into two large monophyletic groups. The first group, ACK-4 (Hiorns et al., 1997) or hgcI (Glöckner et al., 2000), included clusters ACK-M1 and Sta2-30 (Zwart et al., 2002). The second group of Actinobacteria called C111 (Urbach et al., 2001) included clusters Urk0-14, CL500-29 and Med0-06 (Zwart et al., 2002).

As a rule, the proposed cluster should contain at least two sequences that have at least 95% similarity and inhabit deep zones of at least two freshwater bodies. According to these conditions, the Luna cluster was the next sixth proposed cluster belonging to the typical freshwater bacteria (Hahn et al., 2003). The members of this cluster were widespread in various freshwater ecosystems of Europe, Asia and North America, and they contained cultivated members having ultramicrobacterial cell sizes (less than 0.1 μm^3) even when grown in a very rich medium. The isolated pure cultures had cells in the shape of a vibrio.

2.3. Phylogenetic lineages of freshwater Actinobacteria

Warnecke et al. (2004) first proposed a unified classification of freshwater Actinobacteria. Actinobacterial sequences obtained from various freshwater bodies were grouped into four phylogenetic clusters: acI, acII, acIII, and acIV. These phylotypes were stable in different tree reconstructions (neighbour joining, maximum parsimony and maximum likelihood), and they were separated from the soil and marine lineages of Actinobacteria.

The acI and acII clusters were typical autochthonous freshwater Actinobacteria, and the acIV cluster contained only sequences of uncultivated Actinobacteria from freshwater bodies, marine sediments and soil (Warnecke et al., 2004). The acI was separated into three subclusters: acI-A corresponding to the ACK-M1 cluster, acI-B corresponding to Sta2-30 (Zwart et al., 2002) and a new acI-C subcluster (Warnecke et al., 2004). In the acII cluster, the subclusters acII-B and acII-D were identified, corresponding to Luna-1 and Luna-2 (Hahn et al., 2003) and two new groups: acII-A (meromictic lake Sælenvannet, Norway) and acII-C (dystrophic lake Fuchskuhle, eutrophied water body in the Czech Republic and hot springs in New Zealand) (Warnecke et al., 2004). Sequences in the acIII cluster were obtained from chemocline of Lake Sælenvannet (Norway) and corresponded to the sequences of the cluster 2 identified in water of hypersaline soda lake (Humayoun et al., 2003). The acIV cluster was divided into the acIV-A subcluster corresponding to CL500-29 (Zwart et al., 2002) and the acIV-B subcluster (Warnecke et al., 2004).

Newton et al. (2011) supplemented and extended the previous classification by using his data and material accumulated in the databases. Nine freshwater lineages (acI, acTH1, acSTL, Luna1, acIII, Luna3, acTH2, acIV, and acV), including more than 40 clusters, were isolated in the phylum Actinobacteria. Phylogenetic lineages acI, acTH1, acSTL, Luna1, acIII, Luna3, and acTH2 belonged to the orders Actinomycetales and Micrococcales (class Actinobacteria), and the lineages acIV and acV – to the order Acidimicrobiales (class Acidimicrobiia) (Newton et al., 2011; Ludwig et al., 2012; Ghai et al., 2014). The 16S rRNA phylogeny of some freshwater actinobacteria is shown in the figure borrowed from Ghai et al. (2013).

2.4. Characterisation of uncultivated and cultivated representatives of phylogenetic lineages of freshwater Actinobacteria

The abundant and widespread actinobacterial groups in freshwater bodies are acI, acIV and Luna1 (Humbert et al., 2009; Newton et al., 2011; Parveen et al., 2011; Martinez-Garcia et al., 2012).

According to the classification of Newton et al. (2011), acI contains 13 clusters. One of the clusters includes ‘*Candidatus* Planktophila limnetica’, being the first proposed species of Actinobacteria, which was obtained in the mixed culture (Jezbera et al., 2009). Recently, pure cultures of Actinobacteria belonging to acI, which are related to the genera ‘*Candidatus* Planktophila’ and ‘*Candidatus* Nanopelagicus’, were obtained (Kang et al., 2017; Neuenschwander et al., 2018). These two genera formed a new family ‘*Ca.* Nanopelagicaceae’ as well as a new order ‘*Ca.* Nanopelagicales’ that formed in the phylogenetic tree a stable related group together with the orders Streptomycetales, Streptosporangiales and Acidothermales (Neuenschwander et al., 2018). ‘*Candidatus*’ status is given to genera and species until none of the freshwater groups is represented by a taxon with a reliably published name (Hahn, 2009). The genus ‘*Candidatus* Planktophila’ includes six species (‘*Ca.* Planktophila limnetica’, ‘*Ca.* Planktophila dulcis’, ‘*Ca.* Planktophila sulfonica’, ‘*Ca.* Planktophila versatilis’, ‘*Ca.* Planktophila lacus’, and ‘*Ca.* Planktophila vernalis’),

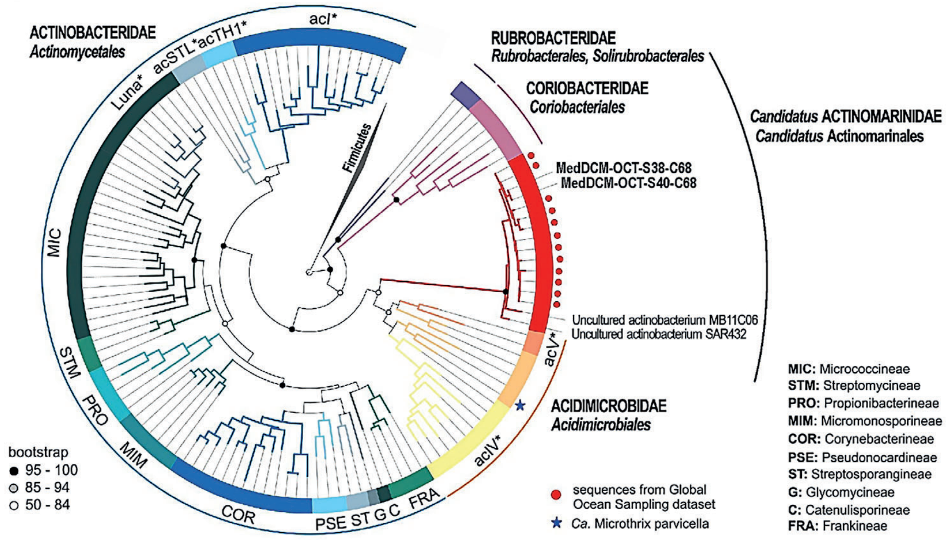

Fig. 16S rRNA phylogeny of some freshwater lineages in the context of the entire Actinobacteria phylum, with Firmicutes as the outgroup. Actinobacterial sub-classes are in bold uppercase and orders in bold italics. Sub-orders are shown in different colors in the tree and labeled (key is shown on bottom right). Freshwater actinobacterial clades are marked with black asterisk. Bootstrap values for all major branches are indicated by colored circles (see key bottom left) (Ghai et al., 2013).

and the genus *Candidatus* Nanopelagicus' – three species ('*Ca.* Nanopelagicus limnes', '*Ca.* Nanopelagicus hibericus'and '*Ca.* Nanopelagicus abundans'). The strains isolated from Lake Soyang (Korea) are two more new species: '*Ca.* Planktophila rubra' and '*Ca.* Planktophila aquatilis' (Kim et al., 2019).

The isolated strains of the genus '*Ca.* Planktophila' and the genus '*Ca.* Nanopelagicus' are aerobic free-living motionless photoheteotrophs. They have a very small cell size (from 0.012 to 0.061 μm3), stream-lined genome (from 1.16 to 1.46 Mb), genome with low G + C content (less than 50%), and carry genes for actinorhodopsins (Kang et al., 2017; Neuenschwander et al., 2018; Kim et al., 2019).

The acIV lineage is divided into four monophyletic clusters (acIV-A, acIV-B, acIV-C, and acIV-D) and six subclusters (Newton et al., 2011). It consists of uncultivated actinobacterial sequences obtained from various environments and includes cultivated strains of Actinobacteria, such as the strain *Ilumatobacter fluminis* YM22-133 isolated from the sediments of the estuary of the Kuiragawa River (Japan) (Matsumoto et al., 2009) and the strain *Aquihabitans daechungensis* CH22-21 (family *Iamiaceae)* isolated from the water reservoir Daechung (Korea) (Jin et al., 2013). These strains are aerobic free-living motionless chemoorganotrophs with a high G + C DNA content (68-72%).

Analysis of the metagenomic sequences obtained from various lakes and estuaries indicated that the genomes acI and acIV have a low G + C DNA content, from 42 to 50% (Ghai et al., 2012). Although Actinobacteria are characterized as organisms with a high of G + C DNA content, both types of Actinobacteria together inhabit freshwater bodies.

The Luna1 lineage consists of four clusters, one of which, Luna1-A2, is the most numerous in the database of sequences (Hahn, 2009). New species of the isolated Actinobacteria belonging to this lineage and having '*Candidatus*' status formed two Luna clusters. The name Luna originates from the name of Lake Mondsee (Moon Lake, Austria), from which the first strains of freshwater Actinobacteria with selenoid morphology (vibrio) were isolated (Hahn et al., 2003; Newton et al., 2011).

The first cluster Luna-1 (the Luna1 lineage) included strains with red pigments, such as '*Ca.* Rhodoluna lacicola', '*Ca.* Planktoluna difficilis', '*Ca.* Aquiluna rubra', '*Ca.* Rhodoluna limnophila', '*Ca.* Rhodoluna planktonica', and '*Ca.* Limnoluna rubra', as well as one strain with yellow pigment, '*Ca.* Flaviluna lacus' (Hahn, 2009). Based on phylogenetic, phenotypic and chemotaxonomic features, the obtained '*Ca.* Rhodoluna lacicola' strain is a new species *Rhodoluna lacicola* of the new genus *Rhodoluna* within the family Microbacteriaceae and order Micrococcales (Hahn et al., 2014). Another IMCC13023 strain belonging to '*Ca.* Aquiluna rubra' was first isolated from seawater; then the similar 16S rRNA gene sequences with 99% homology were also found in freshwater bodies (Kang et al., 2012). Unlike other known members of the family Microbacteriaceae, the strains *Rhodoluna lacicola* and IMCC1302 have ultra-micro sizes, a reduced genome (1.43 and 1.359 Mb, respectively) and low content of GC base pairs in DNA (51.5-51.7%) (Kang et al., 2012; Hahn et al., 2014). The remaining strains from the Luna-1 cluster had the *Candidatus* status because they were obtained only in mixed culture with other non-actinobacterial strains (Hahn, 2009).

The second cluster Luna-2 (the acIII lineage) included only strains with yellow pigments, which had an unknown species status (Hahn et al., 2003).

Other lineages of freshwater Actinobacteria are minor and found only in some water bodies. The acV lineage is associated with bacteria isolated from soil, and it clusters with the soil group SoilII + III. The acSTL, acTH1 and acTH2 lineages do not have cultivated representatives and consist of clones obtained from the water of Lake Stechlin in Germany (acSTL) and Lake Taihu in China (acTH1 and acTH2) (Wu et al., 2007; Newton et al., 2011). Luna3 is closely related to other Luna groups but still also consists of uncultivated representatives.

In addition to the above, new groups of photoheterotrophic planktonic Actinobacteria were identified within the already known freshwater lineages. These Actinobacteria had a reduced small genome (1.16-1.32 Mb) and different G+C content (from 44 to 61%) as well as possessed proteorhodopsins and actinorhodopsins (Ghai et al., 2014). These are the acMicro group in the acIII lineage (order Actinomycetales) and the acAcidi group in the order Acidimicrobiales.

2.5. Phylogenetic groups of freshwater Actinobacteria in Lake Baikal

In Lake Baikal, phylum Actinobacteria is one of the dominant groups (Parfenova et al., 2013; Zakharova et al., 2013; Gladkikh et al., 2014; Krasnopeev et al., 2016; Kurilkina et al., 2016; Bashenkhaeva et al., 2017; Cabello-Yeves et al., 2018; Kulakova et al., 2018), comprising approximately 30% of bacterioplankton (Parfenova et al., 2013; Bashenkhaeva et al., 2015; Mikhailov et al., 2015) and during spring blooming of phytoplankton – up to 57% of the bacterial community in the water column (Mikhailov et al., 2019), up to 14% of the microbial community of the endemic sponge *Lubomirskia baikalensis* (Gladkikh et al., 2014) and up to 44% of bacterial community in the lake sediments (Zemskaya et al., 2015).

Glöckner (2000) first discovered freshwater Actinobacteria in Lake Baikal. Molecular approach enabled identifying in the water column the species *Planktophila limnetica* (acI) typical of bacterioplankton (Parfenova et al., 2013; Gladkikh et al., 2014), the orders Actinomycetales and Acidimicrobiales as well as other unclassified Actinobacteria (Mikhailov et al., 2015; 2019). The genus *Planktophila* and the order Acidimicrobiales were found in all species of healthy Baikal sponges (Seo et al., 2016), and the representatives of the genera *Ilumatobacter* and *Iamia* (acIV) were identified in diseased sponges *L. baicalensis* and *Baicalospongia intermedia* (Krasnopeev et al., 2016). In the sub-ice waters, there were Actinobacteria of the genus *Ilumatobacter* (acIV) (Bashenkhaeva et al., 2015), freshwater acI ones, the acAcidi group, the family Acidimicrobiaceae and other unclassified Actinobacteria (Bashenkhaeva et al., 2017; Cabello-Yeves et al., 2018). Actinobacterial sequences of the genus *Ilumatobacter* were also detected in the deep near-bottom layers in the lake (Zakharova et al., 2013). In gas- and oil-bearing sediments, Actinobacteria belonging to the acI (family Sporichteaceae, hgcI group) and acIV (family Acidimicrobiaceae) were identified (Zemskaya et al., 2015).

To date, no strain of the known freshwater lineages of Actinobacteria has been isolated from Lake Baikal.

3. Conclusion

Therefore, over two past decades since the discovery of the first freshwater Actinobacteria, nine monophyletic freshwater lineages belonging to the classes Actinobacteria and Acidimicrobia within the phylum Actinobacteria have been identified. Pure and mixed cultures of Actinobacteria belonging to different freshwater lineages, such as acI, acIV, Luna1, and acIII, have been obtained. Another new order, '*Ca.* Nanopelagicales', within the class Actinobacteria has been proposed. The presented unified classification is not final and is being supplemented. Further studies to identify new phylogenetic groups of actinobacteria in freshwater environments and to isolate and cultivate new previously uncultivated representatives of freshwater Actinobacteria are promising, necessary and important because they form the basis for subsequent ecological research on the role of freshwater Actinobacteria in the natural habitat.

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Baikal endemic sponges in the system of ecological monitoring

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ABSTRACT. Within the framework of the monitoring of the Baikal endemic sponge fauna, which was started in 2015, we organized field observations. This study is aimed to investigate the dynamics of the disease incidence in sponges and the rate of their degradation/regeneration in the natural environment within a limited space. The observations of the tagged sponges having different shapes were carried out using the photo and video method. Thus, from 2016 to 2018, there was a deterioration dynamics in the state of most control sponges. From 2018 to 2019, the state of some sponges improved owing to the regeneration of the affected areas of the body. In this study, we revealed that Baikal sponges with encrusted and globulous shapes could recover very quickly owing to the regeneration of the affected areas and the rapid growth of the body. After almost complete degradation of the body in the encrusted sponge, the fragments remain, which can subsequently grow as individual specimens. Similar observations are currently being conducted throughout Lake Baikal.

Keywords: sponge mortality, tagged (marked) sponges

1. Introduction

Sponges play a significant role in the ecosystem of any water body. They serve as the habitat for many organisms and are important in benthic-pelagic interaction due to their impressive filtration activity. Sponges provide extraordinary flows of matter and energy; at sites of their accumulation, there is a large species diversity of organisms (Maldonado et al., 2015). They process a solid substrate, accelerating bioerosion, and are involved in the processing of organic compounds of primary production through microbial symbionts (Bell, 2008). Currently, there are 7 families, 47 genera and 236 freshwater species in the World sponge fauna (Manconi and Pronzato, 2019). In Lake Baikal, 15 species of the endemic family Lubomirskiidae and 5 species of the cosmopolitan species Spongillidae have been described (Efremova, 2001; 2004; Itskovich et al., 2017; Manconi and Pronzato, 2019; Bukshuk and Maikova, 2020). Baikal endemic sponges are an example in the formation of the bouquet of closely related but morphologically different species that are adapted to the unique conditions of a deep-water lake. According to the visual observations of I.V. Khanaev and some publications (Kozhov, 1972; Masuda, 2009; Efremova, 2001; 2004; Bukshuk and Timoshkin, 2013), sponges are adapted to inhabit a wide range of depths, from 1.5 to 1540 m. Although the species composition of sponges in Lake Baikal is small in comparison with other representatives of zoobenthos, they are a constant and very significant component of bottom communities (Kozhov et al., 1969). The bulk of their abundance and species diversity is at depths of 3-40 m (Efremova, 2004; Masuda, 2009). This depth range concentrates the main species diversity of many benthic organisms, and this zone is currently experiencing the greatest changes indicating an increasing anthropogenic load (Kravtsova et al., 2012; 2014; Kobanova et al., 2016; Timoshkin et al., 2016). Attached sponges are very stressed when environmental conditions change. Stress can affect the physiological state of sponges, which entails the loss of control over microbiome and, consequently, the development of diseases (Pita et al., 2018).

Information about the disease of marine sponges first appeared approximately 100 years ago. At that time, losses of commercial sponges due to the diseases reached 95% in some areas (Smith, 1941). The first data on diseased Baikal sponges were published in 2011 (Bormotov, 2011). At present, diseased sponges are found in all three basins of Lake Baikal (Timoshkin et al., 2016; Khanaev et al., 2018). These data on the disease of freshwater sponges were the first in the world literature; though in marine ecosystems this problem has been already existing for decades.

In 2015, comprehensive monitoring of the state of sponge fauna in Lake Baikal was organized. Along the transects laid in all three Baikal basins, the projective cover of the bottom with healthy and diseased sponges were measured and their species diversity and state were evaluated. We used the underwater photo and

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video method that is widely used to monitor the state of attached animals. Additionally, we used the tagging of single (separate) sponges, which is also widely used to study corals and sponges, including monitoring the rate of the disease progression (Hill and Wilkinson, 2004; Sweet et al., 2015; Precht et al., 2016). In 2015, based on the library materials, freeze-frame data and videos of the Baikal bottom, the number of the affected sponges ranged from 2.4 to 19.1%. The proportion of the affected branched sponges was higher (from 8.5% to 63.3%) than that of encrusting ones (from 0.5% to 17.9%). Sponges are diseased throughout the lake; however, in Listvennichny Bay, the anthropogenic factor significantly aggravates the situation. Here, the lesion of branched sponges is 100%, encrusted sponges – up to 50% and globulous sponges – 38% (Khanaev et al., 2018).

In addition to the transects, the monitoring system of the state of the Baikal sponge fauna includes field observations at the site located in Bolshiye Koty Bay opposite Varnachka Valley (Fig. 1). This study aims to investigate the dynamics of disease incidence in sponges and the rate of their degradation/regeneration in the natural environment within a limited space.

2. Materials and methods

A natural site of the sponge state observations was organized on 4 June 2016 opposite Varnachka Valley, 170 m from the water's edge (the edge coordinates are51º54´07,3´´; 105º06´20,2´´), at depths of 10-11 m. White stones indicated the boundaries of the site. The area of the site is approximately 6 m^2 (Fig. 1). For the observation site, we chose a section of the bottom in Baikal having an outcrop ridge separately rising from the main slope, with minor affected sponges of different body shapes: globulous, encrusted and branched.

The projective cover of the bottom with sponges (the percentage of sponge cover relative to the total area of the site) was calculated using the ImageJ programme by photographs taken in opposite angles on the day of the site organization.

For regular video filming, seven specimens were randomly selected and tagged within the boundaries of the site: two globulous, three encrusted and two branched sponges. Tags were made of rubber and had a round form with a diameter of 20 mm; they were attached to the sponges by thin stainless steel nails. Each tagged sponge had a number (Table 1). To assess the progression of the disease lesion, the tagged sponges were monitored in the field using photographs. SCUBA divers took photographs every year in June.

The degree of lesion or degradation of the sponge body was assessed visually by photographs using scoring system (Easson et al., 2013; Maldonado et al., 2015): 0 – no signs of lesion, 1 – start of lesion, point lesions of the body (lesion occupies approximately up to 20% of the body), 2 – continued lesions (less than 50% of the body), 3 – severe lesion (more than 50% of the body); 4 – degradation of the specimen (to its complete or partial disappearance).

Fig. 1. The site with sponges; white stones indicate the boundaries.

3. Results and discussion

On 4 June 2016, the projective cover of the bottom with sponges of all shapes was 26-36 % (Fig. 1).

Table 1 shows the list of tagged sponges with a description of the lesion development (in points). Throughout the entire observation period (from 2016 to 2019), only one branched sponge under the number VB-2 lacked the disease or any lesion. Other branched sponge, VB-1, had stable point lesion of the body (1 point). Over four years, the lesion degree of the body surface in this sponge did not exceed 20%, which probably indicates some stability and resistance to disease.

Table 1. Description of the lesion degrees in the tagged sponges using a scoring system

Number and body shape of a specimen	State of a specimen			
	in 2016	in 2017	in 2018	in 2019
VB-1, branched	1	1	1	1
VB-2, branched	0	0	0	0
VG-1, globulous	0	1	2	1
VG-2, globulous	0	0	1	0
VE-1, encrusting	0	2	4	4
VE-2, encrusting	0	0	1	0
VE-3, encrusting	0	0	1	0

In three sponges (globulous VG-2 as well as encrusted VE-2 and VE-3) point lesions of the body (1 point) appeared after two years (in 2018), but already in 2019, there was tissue regeneration of the affected areas. Similar processes were also observed in another globulous sponge, VG-1. The first point lesions of the body surface (up to 20%) in this sponge were recorded in 2017, and in 2018, lesions affected 50% of the body surface, but already in 2019, the affected areas reduced and were again up to 20% (Fig. 2). In other words, the rate of the relative recovery of affected areas owing to tissue regeneration and growth of encrusted and globulous species is sufficiently high. In 2019, we observed not only partial regeneration of the affected areas but also covering the tag with a sponge (overgrowing of the tag with a sponge).

Figure 3 shows the encrusted sponge VE-1. This sponge had no lesions of the body when the observations were organized (in 2016); in 2017, a significant part of the body was degraded (ca. 50%) compared to the initial state. In 2018, the sponge degraded almost completely; only small separate fragments of the body remained. It is possible that in the future each of them will be able to grow as an independent specimen. Therefore, by 31 July 2019, among the tagged sponges at the observation site, one specimen (VE-1) degradated.

4. Conclusions

In general, at the beginning of the observations (June 2016), we ascertained a sufficiently good state of control sponges (among seven control sponges, only one had initial signs of the lesion) at the observation site. A year later, in June 2017, we observed a slight deterioration in the general state associated with the addition of one more sponge having initial signs of the lesion (VG-1) and worsening of the state of the encrusted sponge (VE-1). After another year, in June 2018, the deterioration in the state continued: in five sponges, the lesion degree worsened (in globulous and encrusted sponges), and in two branched sponges, the lesion degree did not change. In 2019, we observed a slight improvement in the state of control sponges compared to 2018: four sponges (two encrusted and two globulous) had changes in the lesion degree resulted from the regeneration of some affected areas of the body; in two branched sponges, the lesion degree did not change. Of course, we cannot assess the state of the entire sponge fauna in the lake by the state dynamics of the studied sponges. This requires similar observations throughout Lake Baikal, at sites with the highest abundance of sponges.

Long-term field observations of the state of sponge fauna have revealed that sponges of any shape inhabiting Lake Baikal can be affected. Regardless of the lesion degree, sponges are capable of regenerating or degrading to complete disappearance. Moreover, fragments of the body remaining after degradation of encrusted sponge can subsequently grow as independent specimens.

The results of the observations of separate Baikal sponge specimens are the first in the system of monitoring that we started in 2015. There are still tagged sponges in other areas of the lake. These studies are being continued and will more completely elucidate the dynamics of changes in the state of the Baikal sponge fauna.

Acknowledgements

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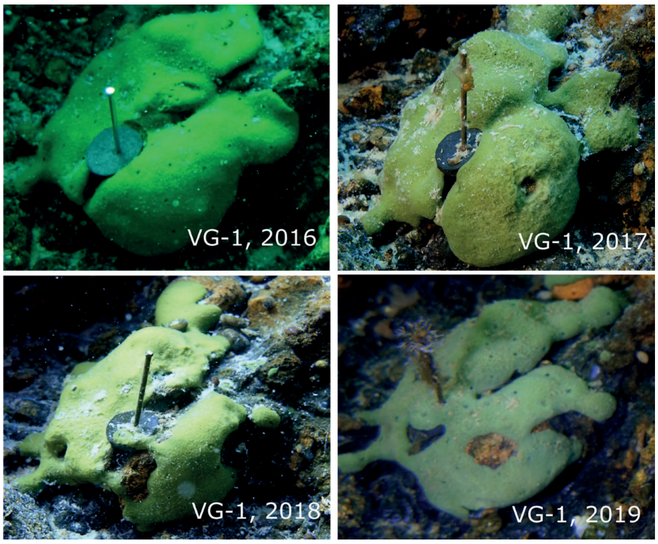

Fig. 2. Development dynamics of the lesion degrees over the years in the globulous sponge VG-1.

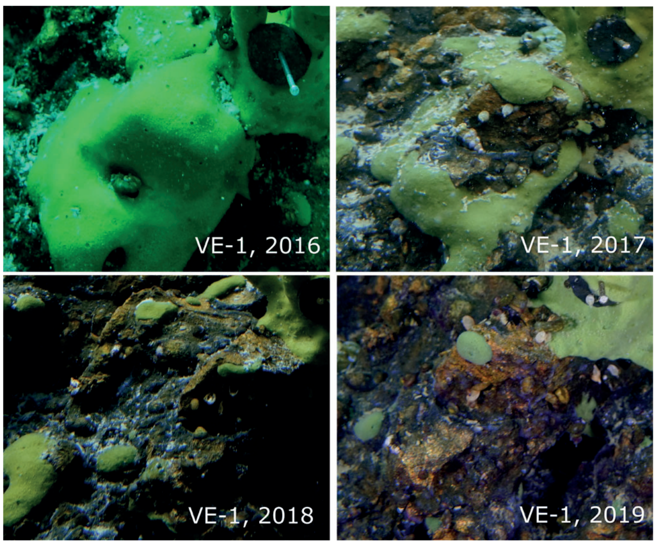

Fig. 3. Development dynamics of the lesion stages over the years in the encrusted sponge VE-1.

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The Gydratny Fault zone of Lake Baikal

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ABSTRACT. The Central basin of Lake Baikal is intersected by the North-East – South-West-oriented escarpment named the «Gydratny Fault zone». This laterally extensive structure runs subparallel to the North-Western shore of the lake. The Gydratny Fault zone has been investigated using geophysical techniques during 6 years of research in the framework of international expeditions of the Class@Baikal project. The acquired seismic data provided details of the structure of the upper part of the sedimentary section revealing a system of previously unknown faults. A new tectonic scheme of the South-Western deep-water part of the Central basin is presented. The Gydratny fault is accompanied by a system of numerous synthetic and antithetic normal faults that form a wide and extended faulted zone. These structures are unevenly distributed, and include modern and active faults as well as features buried under undeformed sedimentary units with different thickness. This parameter is used to constrain the patterns observed in several zones of the study area. The difference in the characteristics of faults and their manifestations on seismic data can be explained by complex and uneven distribution of active tectonic and sedimentary processes.

Keywords: Lake Baikal, Baikal rift zone, seismic survey, neotectonic

1. Introduction

Lake Baikal is located in the Central segment of the Baikal rift system. It is a zone of junction of the East Siberian platform and the Sayan-Baikal mobile belt. The Baikal basin is the oldest and largest element of the rift system. The age of the basin has been broadly debated and suggested to be 25-30 Ma (Hutchinson et al., 1993; Zonenshain et al., 1995; etc.) or 60-70 Ma (Logachev, 1974; 2003; Nikolaev, 1998; Mats et al., 2001; etc.). The long development of the Baikal rift involved the change of sources and stress vectors (Mats, 2015) leading to a complex system of tectonic faults.

The tectonic studies of South Eastern Siberia and adjacent territories date back to the 60s and numerous alternative maps have been proposed (Solonenko, 1965; Sherman, 1977; Levi, 1997; 2002; etc.). The first tectonic schemes of the Baikal subsurface were proposed after structural-geological and seismic studies completed during 1989-1994 (Levi, 1995). Later, they were reviewed and updated, based on the same geophysical data and using additional seismic data (Levi, 1997; Seminskiy et al., 2001; Logachev, 2003; Lukhnev et al., 2013; Lunina et al., 2014; Lunina, 2016) (Fig. 1).

The results of international expeditions of the Class@Baikal project in 2014-2019 allowed to advance in the detailed mapping of tectonic faults.

Between 2014-2019, the Class@Baikal international program acquired ~2000 km of seismic profiles from the Central basin of the Lake Baikal (Akhmanov, 2018). This major achievement doubles the data volume of all previous surveys (Fig. 2b) and allowed to detect and map a large system of modern faults in the South-Western part of the Central Baikal basin. Our new data led to a review and significant improvement of existing schemes of tectonic features.

2. Morphology of the bottom relief

The research area occupies the South-Western deep-water part of the Central Baikal basin (Fig. 2a). The bathymetric map of the area shows a large escarpment in the bottom relief: This feature extends from Cape Uhan on the Olkhon Island towards the South-West for almost 30 km (Fig. 2b, Fig. 2d). Its height gradually decreases towards the South-West declining from 100 to 0 meters. The structure was described by Kuz'min in 2004 based on echo sounder measurements, although

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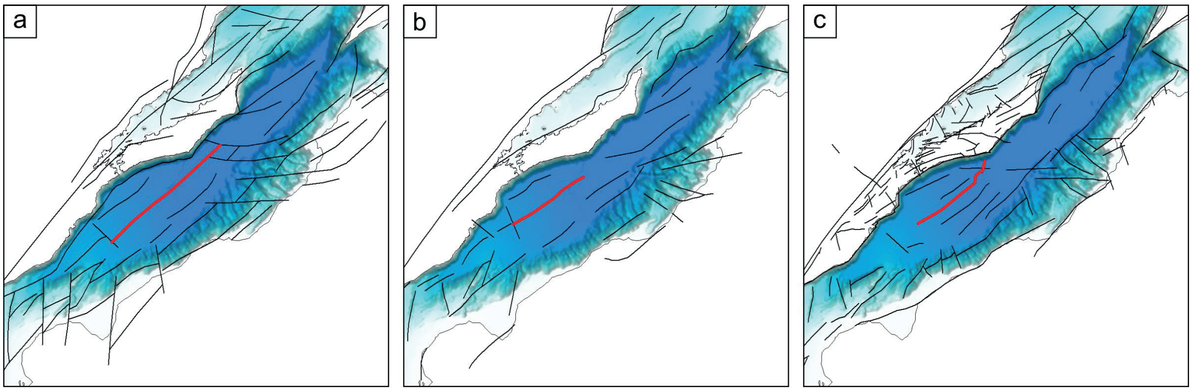

Fig. 1. Tectonic schemes of the Central Baikal basin: (a) by (Levi, 1997); (b) by (Logachev, 2003); (c) by (Lunina, 2016)

its geometry and characteristics were obtained in 2002 during a side-scan sonar and a multibeam echo sounder survey completed in the framework of the INTAS international project (De Batist et al., 2002). In 2009, multibeam bathymetric studies were conducted in the framework of the LIN SB RAS (Russia) and RCMG (Belgium) international project (Bathymetry data…, 2009). These data allowed improving the detail of the digital model of the bottom relief and more accurately to determine the position and the morphology of the scarp.

Numerous structures of focused hydrocarbon gas discharge and near-surface gas hydrates accumulations are associated with this tectonic scarp. For this reason in 2018 was proposed to name this structure Gydratny fault, i.e. Gydratny as «gas hydrates bearing» (Khlystov, 2018).

The bottom relief defining the Gydratny fault is irregular and is represented by curved segments that bend towards the North-West. The North-Western raised block (*block 1*) is characterized by an uneven distribution of slope directions. Its South-Eastern flank is raised relative to the Central part of this block (Fig. 2c). Therefore the azimuths of the slope directions take a predominantly Northern and North-Western direction. This block is adjacent to the Olkhon and Near-Olkhon tectonic blocks, which are sitting at lower bathymetry relative to the uplifted Primorsky Ridge along listric normal faults (Levi, 1995). Their South-Eastern block flanks are also being elevated relative to the North-Western ones (Fig. 2c). Listric faults are quite typical for the tectonic structure of the Olkhon Island and its adjacent areas (Levi, 1995). In agreement with the general tectonic setting and the similarity with the neighbouring tectonic blocks and faults, the Gydratny fault can also be considered as a listric normal fault. The lowered block is characterized by the presence of secondary multiple small faults on the hanging wall (synthetic and antithetic), which were mapped during Class@Baikal expeditions (Fig. 3a, Fig. 3c).

3. Material and methods

The existing database of geophysical data collected during 1992-2002 was complemented with new seismic profiles collected during the 2014-2019 Class@Baikal expeditions (Fig. 2b).These geophysical surveys were carried out using the method of continuous seismic-acoustic profiling using an electric spark source («sparker») with a central frequency of 300 Hz and a chirp profiler with linear modulation of frequencies from 1 to 10 kHz. This methodology of two-frequency surveys allowed us to study near-surface deposits (upper 30 meters) with a high resolution and also to obtain data of the sedimentary section to a depth of about 300 m below the lake floor.

The analysis of the wave pattern on the seismic sections allowed to investigate sediment structures and to trace faults locations. Faults were detected by characteristic kinematic and dynamic features, such as: discontinuity and displacement of the reflectors, a sharp lateral change in the wave pattern, the formation of diffracted waves, and a decrease in the amplitude and frequency of the reflected signal.

Each one of the identified faults was scrutinized for the following criteria: a) the location of the hanging wall and footwall relative to fault, b) the vertical amplitude of the sediment displacement and c) the depth at which the displacement is observed (i.e. the thickness of undisturbed sediments covering each fault) (Fig. 3). Neighbouring faults with similar characteristics were traced in the seismic profiles. This approach allowed to compile a detailed scheme of tectonic faults in the upper part of the sediment section.

4. Results and discussion

The newly detected and mapped tectonic faults are interpreted as branching off from the main Gydratny fault. The map catalogue is summarized in Fig. 4. The study area can be divided in two main blocks (hanging wall and footwall, separated by the Gydratny fault), which can be partitioned into 6 zones with fundamentally different geological structure.

The first block (footwall, *block 1*) is bounded on the North-West by the Obruchev (Olkhon) fault and on the South-East by the Gydratny fault (Fig. 2c). It is a large tectonic block, is essentially undisturbed by tectonic faults and is raised relative to the *block 2*. *Block 1* can be divided into two zones. The whole North-East part (*zone 1A*) is a tectonically undisturbed block where no faults can be observed in the upper 300 m of sediments. Bordering this zone, the portion of Gydratny fault forms a well-expressed scarp in bottom relief. This

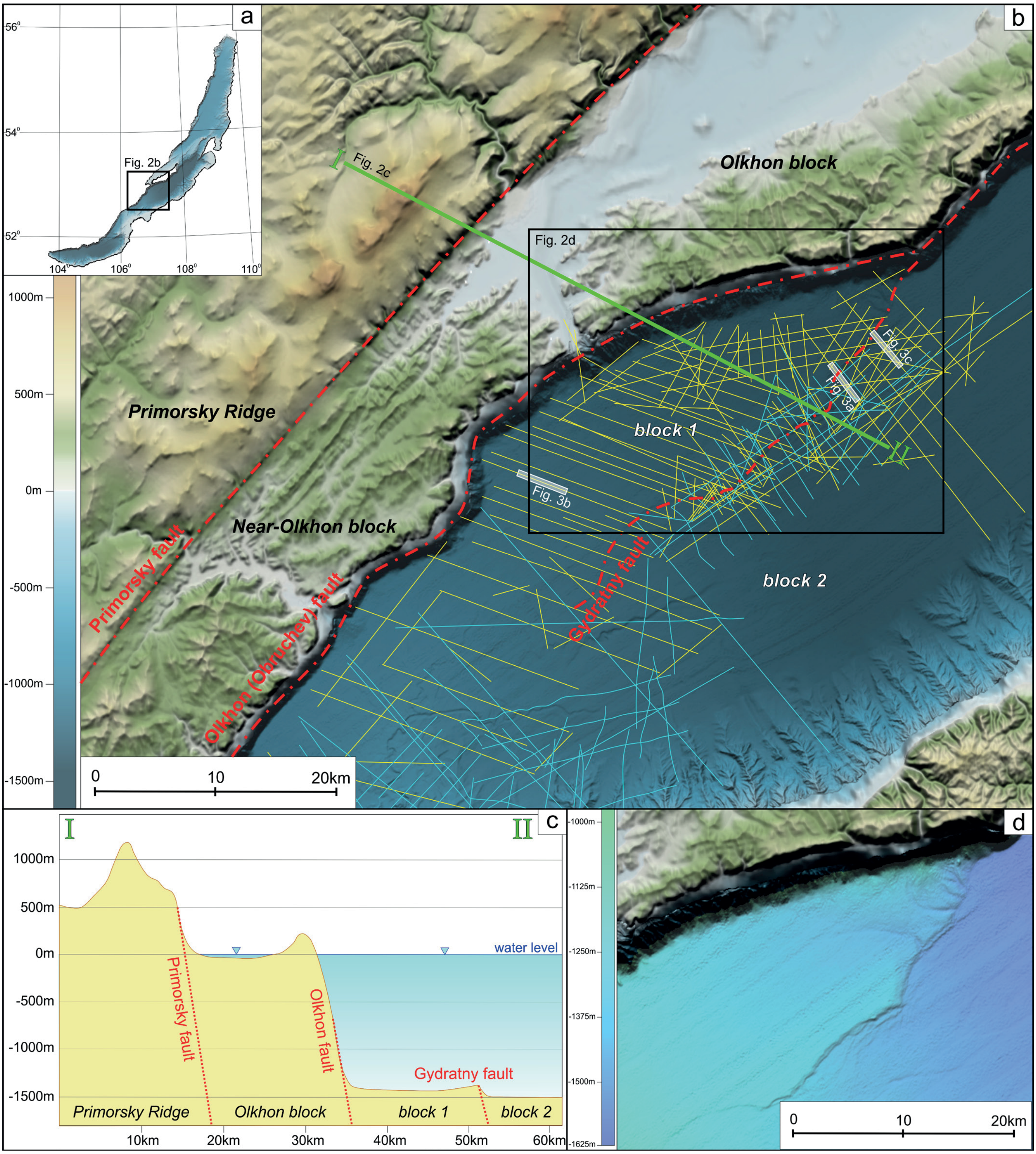

Fig. 2. Overview scheme of the relief in the study area near the Gydratny fault. (a) Lake Baikal with the location of the research area (black polygon); (b) A scheme of seismic data obtained in the Class@Baikal project expeditions in 2014-2019 (yellow lines) and previous surveys in 1992-2002 (blue lines). White frames show the location of fragments of seismic profiles shown in Fig. 3. Green line shows the location of the profile I-II of the bottom relief schematized in panel c. The black polygon frames the area with detailed bathymetry (panel d), where the Gydratny fault is well expressed in the bottom relief. Bathymetry data: LIN SB RAS and RCMG-RAS Program 17.8 (2009) and FWO Flanders Project (1.5.198.09).

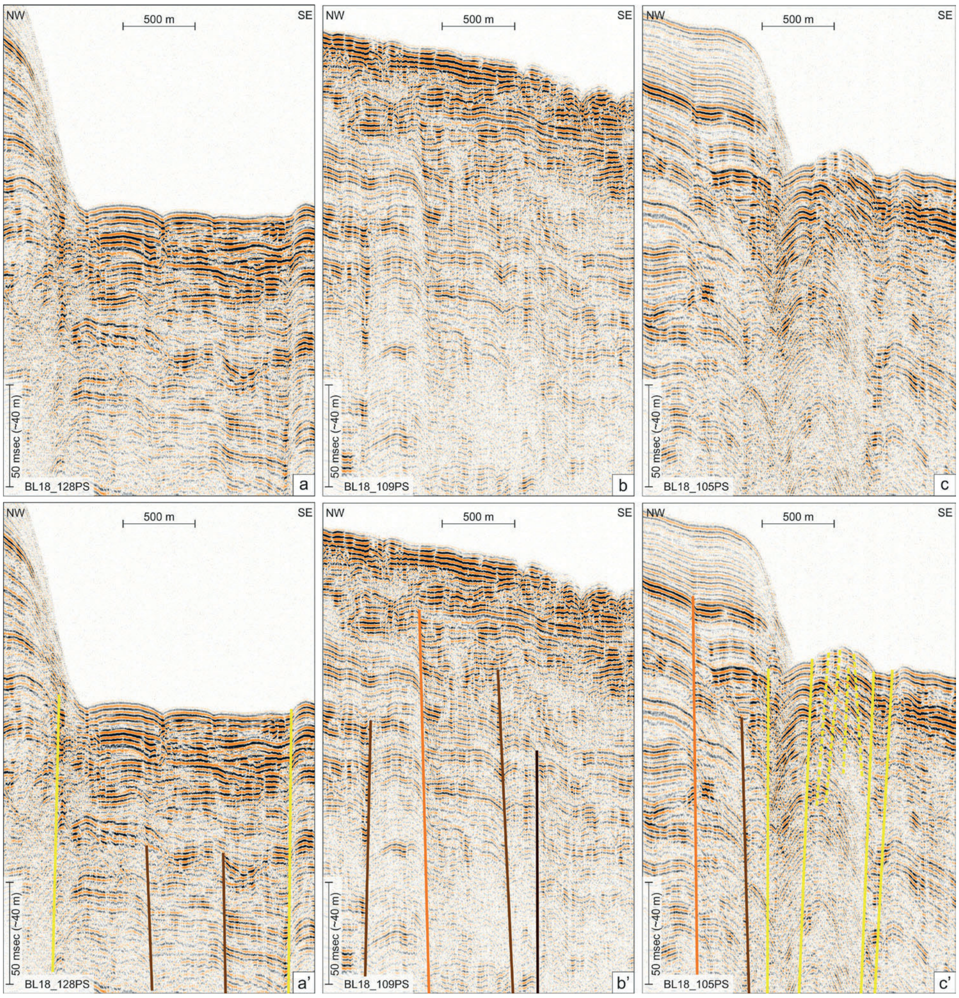

Fig. 3. Examples of identifying tectonic faults on seismic data with fault typization based on the thickness of overlapping sediments. Upper row: seismic sections without interpretation; the lower row: seismic sections with elements of interpretation. Yellow lines show faults that reach to the lake floor (type α), while the other coloured lines indicate faults covered by sediments with a thickness of about 10-40 m (orange lines, type β), 40-85 m (light brown lines, type γ), over 85 m (dark brown lines, type δ). The location of the profiles fragments is shown in Fig. 2b.

zone is characterized by North-West azimuth of the slope directions.

The neighbouring zone of the first tectonic block (*zone 1B*) is located in the South-Western part of the study area and is also bounded by the Olkhon and Gydratny faults. A system of five deep faults covered by thick layers of sediments (up to 150 m) can be traced here. These form a graben-like structure elongated in North-East direction. The amplitude of the sediment displacement reached up to 40 meters.

The second block (hang wall, *block 2*) occupies a broad area in the deep-water part of the lake. It adjoins to the Gydratny fault at the North-West and bounded on the South-East by the foot of the slope of the Central Baikal basin. This area is characterized by extensive faulting. These faults are mostly parallel to the Gydratny fault and accordingly also extend from the South-West to the North-East forming a single wide fault zone (*zones 2A, 2B and 2C*) that extended for 65 km. This heavily faulted region extends from the foot of the Kukuy canyon on the avandelta of the Selenga River to Cape Ukhan on Olkhon Island. We named this zone the Gydratny Fault zone and its width varies from 5 to 11 km. The faults inside this zone form a series of synthetic and antithetic discharges with the lowered South-East and North-West wing respectively. They form several local small grabens in the Central part of this fault zone. All faults are sub-vertical in the upper part of the sediment section and characterized by a distinctly expressed vertical component of movement. Due to the low penetration of the acoustic dataset, the faults roots are not imaged. The amplitude of sediments displacements increases with depth. Most faults are characterized by small amplitudes of sediments displacements in the upper part of the section and they are often replaced by flexures with deformation of layers without their rupture. This may indicate a high plasticity of the sediment or slow displacements along the faults.

All the detected faults are characterized by different location depth on the fault plane. Some structures reached the lake floor, while others are covered by undeformed sediments with different thickness. Using this parameter, all faults were divided into modern active faults (reaching the bottom surface, type α) and 3 groups of faults covered by sediments with a thickness of 10-40 m (up to 50 msec below the lake floor level on seismic sections, type β), 40-85 m

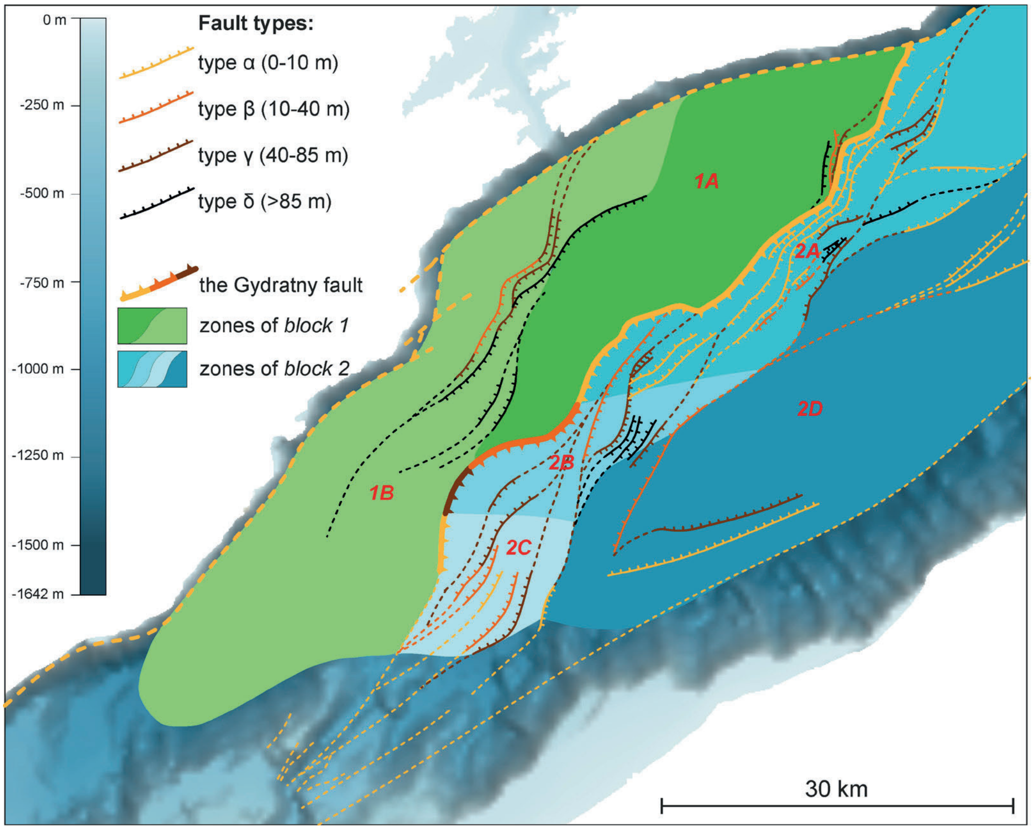

Fig. 4. The scheme of tectonic Gydratny Fault zone with classifying based on the thickness of overlapping sediments. Solid lines show proved established faults, dotted lines show assumed faults. The names of the zones are indicated in red font.

(50-100 msec, type γ) and over 85 m (more than 100 msec, type δ). Moreover, the most laterally extensive faults can reach the lake floor in one portion, and be buried under the modern sediments in the other one.

The different types of faults appear to be distributed irregularly (Fig. 4). In the North-Eastern segment of the Gydratny Fault zone (*zone 2A*), most of the faults reach the lake floor (type α). In the Central segment (*zone 2B*), almost all faults are buried under a thick layers of sediments (mostly types γ and δ). Ultimately the South-Western segment (*zone 2C*) is characterized by a complex combination of faults of different types (α, β, and γ).

This complex pattern can be explained by the multidirectional action of tectonic and lithodynamic processes. This would imply that in the Central and South-West segments (*zones 2B and 2C*) of the Gydratny Fault zone there is a slower displacement along the faults or/and that here are present higher sedimentation rates. Hence in this area can be deposited undisturbed layers of sediments. This scenario is consistent with the observed intensive accumulation of terrigenous material supplied through the Kukuy canyon by the Selenga River (Solovyeva, 2018). Also, slow displacements along the faults are confirmed by presence of flexures above some of faults. The North-Eastern part of the fault zone (*zone 2A*) is characterized by low sedimentation rates due to the large distance from major suppliers of terrigenous material. This probably explains the presence of faults in this area that reach the lake floor.

The Eastern part of *block 2* (*zone 2D*) is characterized by a small spread of faults in the upper part of the sedimentary section. All of the tectonic structures extend sub-parallel to the axis of the Baikal basin and are normal faults with a North-Western lowered wing. The largest amount of modern active faults is also found in the North-Eastern part of this zone.

5. Conclusions

Extensive geophysical investigations conducted in the framework of the Class@Baikal project, allowed us to build a new tectonic scheme for a portion of the Central basin of the Lake Baikal. These newly acquired significantly improve our knowledge of the tectonic setting of this part of the lake revealing a broad and complex system of synthetic and antithetic faults distributed sub parallel to the Gydratny fault. We name this extensively faulted region the Gydratny Fault zone. A detailed classification of the identified faults reveals a complex and uneven distribution of modern active and older buried faults. This pattern is ascribed to the uneven tectonic activity and to the differing sedimentary processes ongoing at the various segments of the Gydratny Fault zone.

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Estimation of the influx of pollutants to the territory of the South Pribaykalye

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ABSTRACT. We present the results of long-term (2010-2017) studies of chemical composition of snow cover from the area of the Baikal Region. There is significant pollution of snow cover in the industrial cities of Pribaykalye (Irkutsk and Shelekhov). Some areas are the most subjected to the atmospheric pollution. The emissions from Shelekhov enterprises influence the chemical composition of snow cover in Irkutsk. Transport, fuel and energy complex mainly influence the formation of the chemical composition in snow cover from Irkutsk. In Shelekhov, the source of contaminants is the aluminium smelter (RUSAL-IrkAZ) and power engineering. Based on the data on snow surveys, we estimated the influx of pollutants from the atmosphere to the underlying surface of industrial cities and the water area of South Baikal.

Keywords: industrial cities, Lake Baikal, snow cover, chemical element concentrations, accumulations, influx from the atmosphere

1. Introduction

According to Voeikov Main Geophysical Observatory, in 2018, the Priority list of Russian cities with the highest level of atmospheric air pollution contained seven cities of the Irkutsk Region, including Irkutsk and Shelekhov. A large amount of contaminants enters the atmosphere from heat power enterprises. Snow cover summarizes emissions for the entire winter period and is an integral indicator of atmospheric pollution (Vasilenko et al., 1985; Lomonosov et al., 1993; Chebykin et al., 2018; Paradina et al., 2019). After melting of the snow cover, the pollutants accumulated over the entire winter period enter the soil and water bodies. Assessment of their influx from the atmosphere with precipitation and dry deposition allows for the calculation of ecological risks to the environment. Under the decision of the UN Economic Commission for Europe, the group of the most hazardous heavy metals includes mercury, lead, cadmium, chromium, manganese, nickel, cobalt, vanadium, copper, iron, zinc, antimony as well as typical metalloids: arsenic and selenium. Of special hazard are metals that are not part of biomolecules, i.e. xenobiotics: mercury, cadmium and lead (Bashkin and Kasimov, 2004).

Almost all industrial production, fossil fuel combustion, transport and other human activities cause anthropogenic dispersion of elements and heavy metals in the environment (Kleeman et al., 2008; Wiseman and Zereini, 2009). Fuel combustion leads to the atmospheric pollution by As, Cr, Cu, Mn, Ni, Sb, Se, V, and Zn; non-ferrous metallurgy – by Al, Ag, As, Cd, Cu, Ni, Pb, Sb, and Zn; ferrous metallurgy – by Cd, Fe, Mn, Ni, Pb, and V (Saet et al., 1990; Berg et al., 2008; Pacyna et al., 2009).

Studies of the chemistry of snow cover in the Irkutsk Region enabled evaluation of the element fluxes from the atmosphere in the Baikal Natural Territory (Anokhin et al., 1981; Kokorin and Politov, 1991; Vetrov and Kuznetsova, 1997; Koroleva et al., 1999; Obolkin et al., 2004; Khodzher, 2005; Onischuk et al., 2012). Geochemical assessment of the state of snow cover in the cities of the Irkutsk Region revealed areas that are most subjected to atmospheric pollution (Lomonosov et al., 1993; Belozertseva, 1999).

The aim of the work is to assess the annual influx of pollutants from the atmosphere to the underlying surface in the cities of Irkutsk and Shelekhov as well as to the water area of Southern Baikal in the modern period.

2. Materials and methods

Snow cover was sampled for its entire height at the end of winter, in February and March. In the water area of Lake Baikal, snow was sampled from the ice in Southern Baikal, being the most subjected to the anthropogenic impact (Fig. 1, Table 1). Fluxes at the

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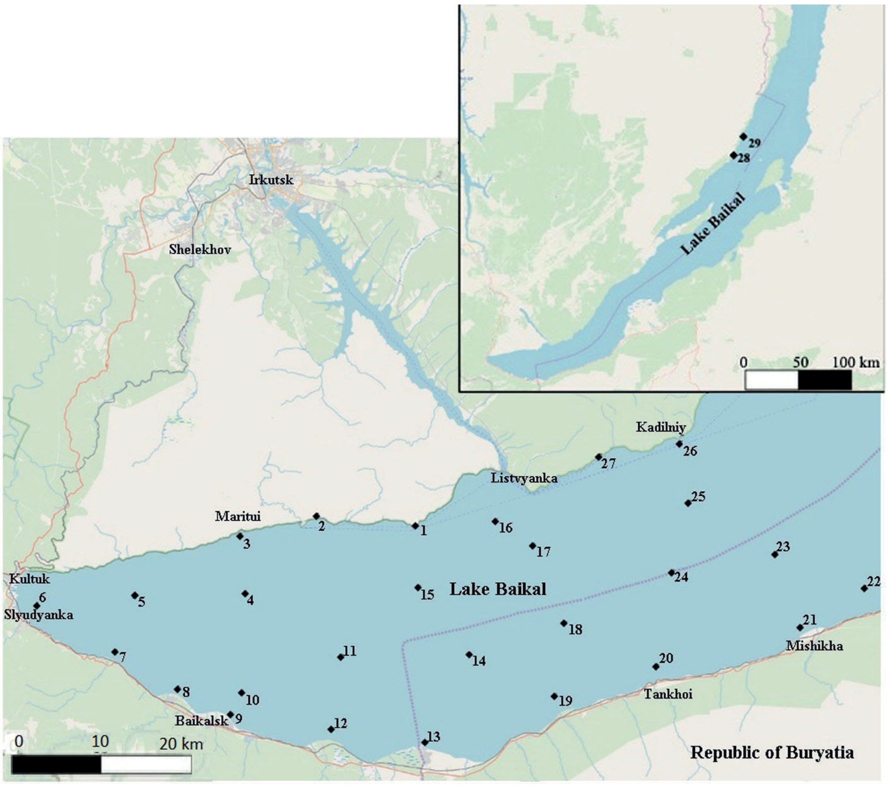

Fig. 1. Map of the sampling locations.

underlying surface were calculated from the averaged values between 2010 and 2015. In the industrial centres, Irkutsk and Shelekhov, located 70-80 km from the Baikal coast, samples were taken episodically from 2000 to 2013 at 20 sampling sites in each city. Snow cover samples were taken at a distance 500 m from the main highways. We took 99 snow cover samples from Shelekhov, 111 samples from Irkutsk and 90 samples from Southern Baikal. The chemical composition of snow cover sampled from the ice of Lake Baikal near the capes Onkholoy and Bolshoi Solontsovy (Baikal-Lena Nature Reserve (BLR), northwest coast of the lake) served as the background. To calculate the accumulation, we used averaged concentrations and moisture content in the snow cover. The moisture content (cm) was calculated as the ratio of the volume of the melted sample (cm^3) of the snow cover to the area (cm^2) from which it was collected.

Chemical analysis of snow water was carried out in the Laboratory of Hydrochemistry and Atmosphere Chemistry (Accreditation certificate No. ROSS RU.0001.513855) at Limnological Institute SB RAS. Concentrations of sulphates and nitrates were determined by ion chromatography (ICS-3000, Dionex, USA) and high-performance liquid chromatograph with UV detection (Milichrome A-02, Ekonova, Russia) (Khodzher et al., 2016). We used standard solutions from the “Kanto Chemical Co” (Japan) and “Ultra Scientific” (USA). Solids of snow water were investigated by the X-ray fluorescence technique using synchrotron radiation (SXRF) at the Institute of Nuclear Physics SB RAS. The element concentrations of water phase were determined on an Agilent 7500 ce quadrupole mass spectrometer in the Ultramicroanalysis Center at the Institute of Limnology SB RAS. The samples were supplied using a microflow sprayer (0.3 mL/min). The instrument was calibrated using a high purity standard solutions ICP-MS-68A-A-100 and ICP-MS-68A-B-100 (1, 2, 5, 10, 25 ppb of each element). The drift of the instrument was monitored using an In internal standard and a control sample (a standard solution with 5 ppb of each element), which was measured in ten sample intervals. Based on the geometric estimation of the spatial distribution of elements, we constructed maps illustrating accumulation of some metals in snow cover. The maps show the total flux of soluble and insoluble forms of metals.

3. Results and discussion

3.1 The Irkutsk city

The study of the chemical composition of snow cover in Irkutsk indicated the highest values of all analysed components near Glazkovo bridge, the Eternal Flame (the Kirov Square), the Paris Commune Park, the Ushakovka River (Rabocheye suburb), Novo-Lenino (area of Cinema college), and Marata suburb.

The most part of these areas is located in low reliefs along the valleys of the rivers Irkut and Angara where meteorological conditions are extremely unfavourable for the dispersion of air pollutants due to low wind speeds typical of lowlands. The above areas experience significant anthropogenic pressure from the industrial objects and roads located here (Novikova, 2015). They are also affected by impurities coming with airflow, which is due to local circulation processes, from Shelekhov along the valley of the Irkut River as well as from Angarsk along the valley of the Angara River.

Table 1. The sampling stations on South Baikal

№	Sampling stations	The coordinates	
		northern latitude	eastern longitude
1	Near the Cape Tolstiy	51°47’36,0”	104°36’62,0”
2	Near the Cape Polovinniy	51°97’85,0”	104°22’87,9”
3	Opposite the Maritui settlment	51°46’44,1”	104°12’56,7”
4	Center of the section Marituy-Solzan	51°41’40,0”	103°57’87,3”
5	Between Slyudyanka town and Maritui settlment	51°41’40,0”	103°57’87,3”
6	Opposite Slyudyanka town	51°40’48,9”	103°44’53,6”
7	Near the Cape Telegraphiy	51°36’49,6”	103°55’39,2”
8	Opposite the Utulik River	51°33’37,8”	104°04’16,1”
9	Opposite the Baikalsk city	51°31’28,4”	104°11’37,6”
10	3 km from the Baikalsk city	51°31’74,9”	104°12’96,2”
11	Opposite the Khara-Murin River	51°36’22,6”	104°26’46,7”
12	Near the Khara -Murin River	51°30’12,1”	104,24’90,6”
13	Opposite the Snezhnaya River	51°29’05,7”	104°37’83,7”
14	From Snezhnaya River to Listvyanka settlment	51°35’97,0”	104°43’87,6”
15	Section the Snezhnaya - Tolstiy	51°41’80,2”	104°36’87,1”
16	Between the Tolsty and Berezovy capes	51°48’00,1”	104°47’63,9”
17	Section Listvyanka-Tankhoy	51°45’53,6”	104°52’70,7”
18	Listvyanka- Tankhoy section	51°39’16,5”	104°57’33,6”
19	Near the Cape Kedroviy	51°32’64,0”	104°56’09,3”
20	The Pereemnaya River, 1 km from the shore	51°34’93,2”	105°10’11,8”
21	The Ushakovka River, 0.5 km from the shore	51°38’55,3”	105°29’67,1”
22	Opposite the River Klyuevka	51°42’17,1”	105°38’55,6”
23	Section the Kadilniy-Mishikha, 10-15 km from Mishikha River	51°44’68,1”	105°26’34,1”
24	Section the Kadilniy-Mishikha, the center	51°43’34,6”	105°12’25,3”
25	Section the Kadilniy-Mishikha, 10-15 km from the cape Kadilniy	51°48’90,0”	105°13’97,6”
26	Near the Cape Kadilniy	51°54’33,2”	105°13’28,5”
27	Opposite the Fall Chernaya	51°53’26,4”	105°02’16,7”
28	Near the cape Onkholoy (Baikal-Lena Nature Reserve)	53°47’46,7”	107°57’32,5”
29	Near the cape Bolshoi Solontsovy (Baikal-Lena Nature Reserve)	54°10’05,7”	108°21’40,2”

The microdistricts located on elevations, such as Zelyony, Raduzhny, Topkinsky, and Solnechny, showed the lowest levels of chemical ingredients in snow cover. These areas are characterized by both high wind speeds, which is normal for elevated surface, and the absence of large sources of anthropogenic impact. From the obtained concentrations, we calculated accumulation of pollutants in snow cover during the cold season. Figures 2 and 3 show the distribution of total accumulation (soluble and suspended forms) of metals in snow cover from Irkutsk.

Average accumulation of trace elements in the soluble fraction, the most aggressive for the environment, was 219 μg/m^2 for V, which is 161 times higher than in the background area (BLR); the accumulation of zinc, copper, arsenic, and barium was 1240, 290, 34, and 2260 μg/m^2, respectively, which is 42, 12, 1700, and 50 times higher than in BLR. The average excess for 20 elements was 220 times in comparison with BLR.

3.2 The Shelekhov city

In snow cover from Shelekhov, the maximum concentrations of the studied elements were detected in the industrial zone near the Thermal Power Plant - 5 (TPP-5) and the RUSAL-IrkAZ aluminium plant. Thus, high concentrations of Be, B, Ti, V, Ni, and Sr were determined in the southwest direction near TPP-5. The highest concentrations of most elements were identified in a small area near the smelter. The maximum concentration Al (27 mg/L) is recorded in the northwest of Shelekhov, near the fifth line of the smelter. This value is at the level determined in the snow cover of Bratsk, Irkutsk region, at a distance of

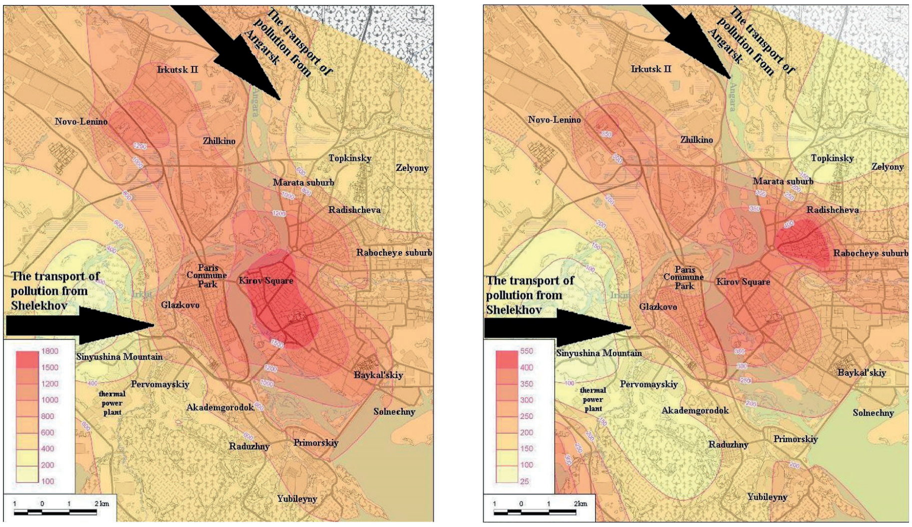

Fig. 2. Copper (left) and lead (right) accumulated in snow cover of Irkutsk, μg/m^2.

0.5 km from the aluminum smelter (20 mg/*L*) and 55 times higher than in Blagoveshchensk, the Far East (Ignatenko et al., 2007; Radomskaya et al., 2018).

Concentrations of Na and F, which are tracers in aluminium production, near the smelter were also high according to our 2013 data, up to 33 and 35 mg/L, respectively. According to (Belozertseva et al., 2015), F concentrations in snow cover were higher, up to 60 mg/L.

The accumulation of elements and their distribution on the earth surface in the modern period is close to that indicated in 1996 (Nechaeva et al., 2004). A large amount of contaminants enters the atmosphere from the TPP-5 located near the aluminium smelter. Figure 4 shows the distribution of copper and lead accumulated in snow cover. The maximums of these elements were recorded near the TPP-5. Atmospheric pollution halos from the emissions of the aluminium smelter and TPP-5 extend to the housing estate in Shelekhov. In the residential area of Shelekhov, aluminium concentrations decrease but 4500 times exceed background values (BLR). Industrial emissions from Shelekhov affect the state of the atmosphere in Irkutsk through the transport of contaminants along the valley of the Irkut River (Fig. 4, Fig. 5).

The average concentrations of all soluble elements, except for Al, are higher (up to 4.5 times) in Irkutsk compared to Shelekhov. Aluminium concentrations in Shelekhov is 60 times higher than in Irkutsk.

Atmospheric deposition causes the formation of multi-element pollution halos around cities in the south of the Irkutsk Region. Moreover, the distribution halos of some elements in snow cover from Irkutsk overlap with the distribution fields of elements coming from Shelekhov (Fig. 4, Fig. 5 right). Sources of pollutants typical of large cities, such as transport as well as fuel and energy complex, mainly influence the formation of the chemical composition in snow cover from Irkutsk. In the city of Shelekhov, the aluminium plant makes the main contribution to atmospheric pollution (77 %), the contribution of TPP-5 is much less - 19%.

In the snow cover from Shelekhov, the accumulation of V in the soluble fraction was 90 μg/m^2, which is 2.4 times lower than in the snow cover from Irkutsk and 70 times higher than in BLR. Accumulation

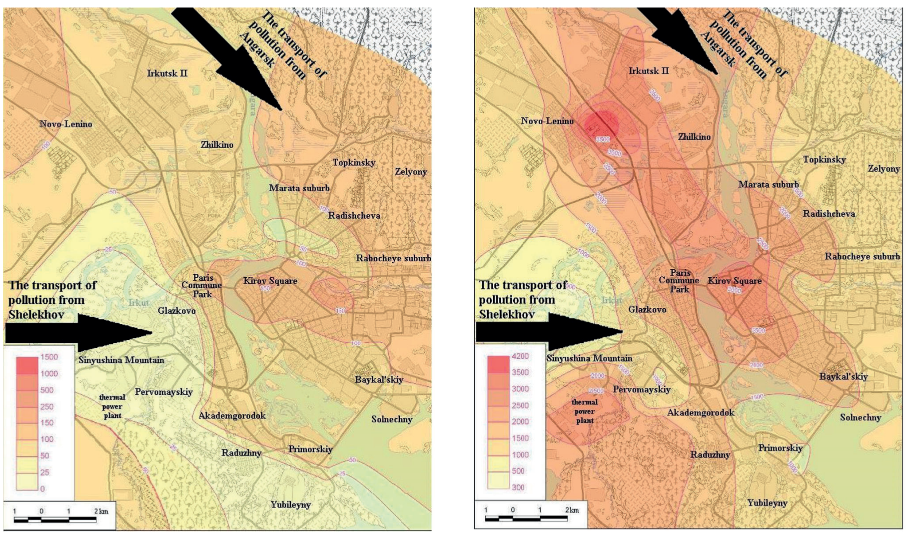

Fig. 3. Aluminium (left) and zinc (right) accumulated in snow cover of Irkutsk, μg/m^2.

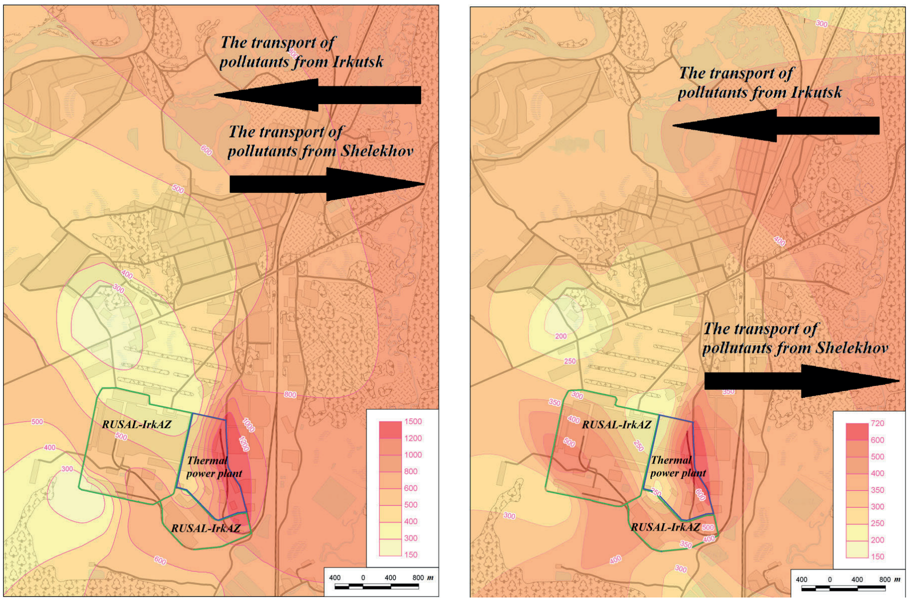

Fig. 4. Copper (left) and lead (right) accumulated in snow cover of Shelekhov, µg/m².

of Zn, Cu and Ba was 570, 100 and 790 µg/m², respectively, which is lower than in the snow cover from Irkutsk. These values are much higher than in the background area, from 5 to 20 times. Accumulation of As in Shelekhov and Irkutsk was the same, with an average of 34 µg/m².

3.3 Snow cover of Lake Baikal

Water in Lake Baikal is low-mineralized, and the content of trace elements in this water is very low (Kulikova et al., 2017). The assessment of the balance of trace elements in the lake should take into account that the significant part comes from the atmosphere (Khodzher, 2005). Due to the prevalence of north-western winds in the region, some part of atmospheric pollution of Irkutsk and Shelekhov can enter the water area of Southern Baikal along the valley of the Angara River. Table 2 shows the concentrations of trace elements, sulphates, nitrates and the total concentration of ions (Σ_i) in snow cover of Irkutsk and Shelekhov as well as on the ice of Southern Baikal. The concentrations of trace elements in snow cover of the cities are one-two orders of magnitude higher than in the lake snow cover.

On Southern Baikal, the maximum concentrations of the studied elements were determined in the sections Kadilny-Mishikha and Listvyanka-Tankhoy. At the central point of the Kadilny-Mishikha section, we determined the maximums of aluminium, iron, nickel, copper, strontium, and barium: 326, 48, 1.6, 3.8, 44, and 20 µg/L, respectively. At the Listvyanka-Tankhoy section, element concentrations were higher than the average value for Southern Baikal (Table 2) and were 203 µg/L for aluminium, 0.87 µg/L for vanadium, 10 µg/L for manganese, 40 µg/L for iron,

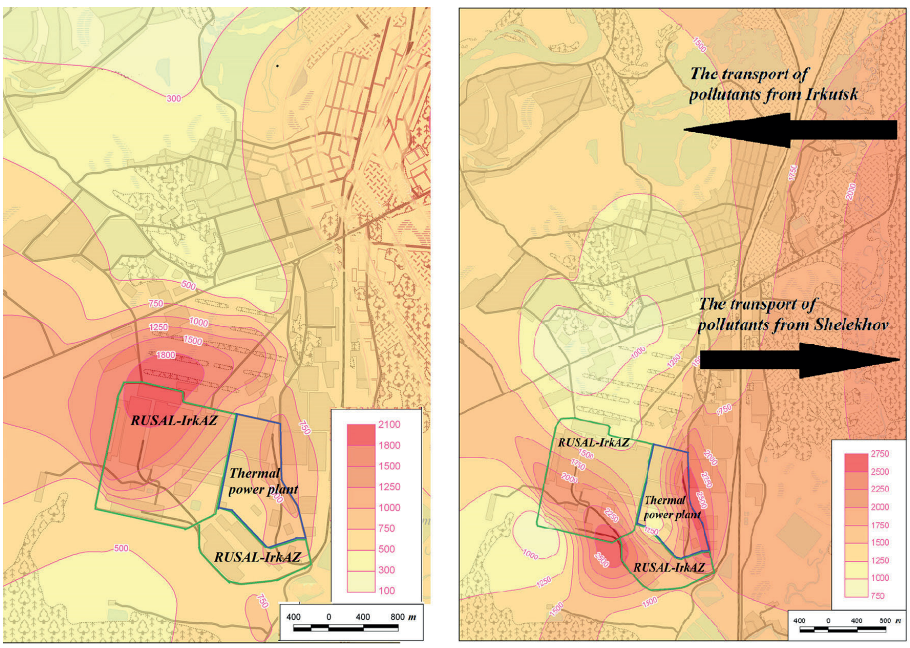

Fig. 5. Aluminium (left) and zinc (right) accumulated in snow cover of Shelekhov, µg/m².

2.1 μg/L for copper, and 41 μg/L for strontium. These are the most likely pathways of transporting air masses from anthropogenic sources located in the influence zone of the Irkutsk-Cheremkhovo industrial hub. High concentrations of the studied elements were also determined on the snow of the lake towns of Baikalsk and Slyudyanka. Currently (the 2017 data), the concentration of sulphates in snow from Baikalsk does not exceed 1.8 mg/L, and Na – 0.18 mg/L, whereas, in 2011, these values were respectively 5 and 15 times higher. The pH values also decreased significantly in the snow cover of the town. In 2011, the maximum pH value reached 8.7 units, and in 2017 – only 6.2 units. At present, Baikalsk and its surroundings show pH values typical of snow cover in the southeast coast of the lake, which is not affected by the large anthropogenic sources, 4.7-5.1 units. However, after the closure of the Baikalsk Pulp and Paper Mill (BPPM) in 2013, the concentrations and accumulation of heavy metals and major ions in snow cover decreased significantly. This indicates a decrease in the anthropogenic pressure on the southeast coast of Lake Baikal.

Comparison of concentrations of the studied elements in snow cover of Southern Baikal and BLR indicated that in the southern basin, element concentrations are six times higher than the background, while Al and Sr show the highest excess in 17 and 14 times, respectively. Considering the wind rose, the snow mostly accumulates on the east coast of the lake; the western part of Lake Baikal is less covered with snow. Therefore, the impact of pollutants from the atmosphere to the east coast is much higher than in the western part of Southern Baikal.

To calculate the influx of elements to surface, we used the data on their average concentrations in snow cover and long-term average annual (2010-2016) amount of atmospheric precipitation in the area of Southern Baikal (the Listvyanka settlement) as well as in Irkutsk and Shelekhov (https://ru.climate-data.org). For Southern Baikal, we calculated fluxes without taking into account the concentrations of sulphates and nitrates in snow cover from Baikalsk and Slyudyanka (Table 3). Comparison of the obtained values showed that amount of sulphates and nitrates entering on the Southern Baikal are respectively 5.5 and 1.5 times lower than ones in the studied industrial cities of the Angara region. However, element fluxes are up to 150 (Al) times higher in the cities. An exception is Pb, whose influx in the area of the Southern Baikal is at the same level as in Irkutsk. Most likely, lead enters the area of Southern Baikal on small aerosol particles due to distant transport from industrial sites. High concentrations of lead were also recorded in other areas of the Earth remote from industrial areas. For example, studies of lacustrine deposits in Antarctica revealed that lead concentrations (obtained from the burning of fossil fuels) have increased significantly, especially over the past 50 years. Alaska shows the same pattern, where lead deposition has become approximately three times higher over the same period (Polar Lakes…, 2008).

Table 3 shows amount of sulphates, nitrates and some trace elements in the water column of Lake

Table 2. Concentrations of pollutants in the soluble fraction of snow cover in 2013, μg/L

Element	Irkutsk	Shelekhov	Southern Baikal	Baikal-Lena Nature Reserve, background
SO_4^{2-}*	8.0-28 13	2.6-27 11	0.85-18 4.83	0.74
$N\text{-}NO_3^-$*	0.49-0.63 0.56	0.38-0.82 0.51	0.35-2.7 0.85	0.19
Σ_i*	21-124 44	9.0-104 42	4.3-41 12.2	2.0
Al	67-251 144	18-26627 8446	6.9-326 101	5.9
V	3.2-13 6.9	0.03-4.2 1.6	0.10-1.3 0.55	0.08
Cr	1.3-3.7 1.9	0.01-16 1.3	0.06-1.7 0.28	0.08
Mn	27-92 62.8	6.86-162 36.9	2.6-24 6.3	1.2
Co	0.4-2.5 1.3	0.01-3.8 0.49	0.02-0.67 0.24	0.04
Ni	2.3-8.8 5.2	0.39-25 3.4	0.29-1.6 0.64	0.11
Cu	1.6-10 6.7	0.25-13 1.8	0.39-3.8 1.8	0.62
Zn	3.2-32 22	0.67-80 11	4.2-35 13	1.79
As	0.26-1.4 0.79	0.06-1.5 0.56	0.01-0.19 0.02	0.001
Se	0.75-1.5 1.2	0.01-2.1 0.36	0.01-0.10 0.04	0.03
Sr	34-108 58	3.0-86 21	3.7-44 14	0.97
Cd	0.08-0.38 0.18	0.001-0.66 0.17	0.001-0.16 0.03	-
Ba	25-60 39	0.14-51 11	5.1-20 8.3	1.88
Pb	0.12-1.0 0.38	0.14-0.98 0.29	0.05-1.7 0.70	0.17

Note - * mg/L; numerator - the minimum and maximum concentrations, denominator - the average concentration

Baikal. Estimates of fluxes were carried out based on the concentrations in the cold season; however, in recent years, due to wildfires, a large amount of aerosol matter has been released in the warm season (Khodzher et al., 2019). Therefore, during wildfires accompanied by atmospheric precipitation and dry deposition, more pollutants can enter the water area of the lake.

4. Conclusion

Long-term studies of element composition of snow cover in large industrial cities of the Baikal region (Irkutsk and Shelekhov) revealed that atmospheric anthropogenic deposition leads to the formation of multi-element pollution halos around these cities. The distribution halos of some elements in snow cover

Table 3. The influx of pollutants from the atmosphere on the South Baikal, Irkutsk and Shelekhov in 2010-2016

Element	Southern basin 7381 km^2		Irkutsk	Shelekhov
	mg/m^2/year	tons	mg/m^2/year	mg/m^2/year
SO_4^{2-}	971 ± 199	7165 ± 1469	5124 ± 787	5363 ± 583
NO_3^-	823 ± 72	6073 ± 531	1287 ± 188	1247 ± 97
Al	29 ± 4	221 ± 30	59 ± 13	4294 ± 233
Cr	0.08 ± 0.02	0.6 ± 0.2	0.55 ± 0.36	0.79 ± 0,55
Mn	1.88 ± 0.16	14 ± 1	20 ± 6	21 ± 1
Ni	0.19 ± 0.02	1.4 ± 0.2	2.8 ± 0.7	1.8 ± 2.8
Cu	0.53 ± 0.04	3.9 ± 0.3	2.8 ± 1.0	0.85 ± 0.64
Zn	6.12 ± 0.32	45 ± 2	12 ± 3	3.8 ± 2.4
Pb	0.21 ± 0.02	1.6 ± 0.2	0.20 ± 0.08	0.14 ± 0.13
Cd	0.009 ± 0.002	0.10 ± 0.02	0.06 ± 0.02	0.08 ± 0.03
Ba	2.50 ± 0.20	19 ± 2	21 ± 5	6.2 ± 8.2
V	0.17 ± 0.02	1.2 ± 0.2	2.0 ± 0.8	0.78 ± 0.18
As	0.006 ± 0.003	0.05 ± 0.02	0.30 ± 0.08	0.27 ± 0.05

from Irkutsk overlap with the distribution fields of elements coming from Shelekhov. Transport, as well as enterprises of fuel and energy complex, mainly influences the formation of the chemical composition in snow cover from Irkutsk. The concentrations of most soluble elements, except for aluminium are higher here than in Shelekhov where the main sources of air pollutants are the aluminium smelter and TPP-5. In comparison with the BLR snow cover, the industrial centres show a significant excess (more than 100 times) of the concentrations and accumulation of such elements as aluminium, vanadium, manganese, nickel, arsenic, and strontium.

Concentrations of most trace elements in snow cover from the southern basin of Lake Baikal are on average six times higher than the regional background values. Anthropogenic impurities enter the water area of Southern Baikal from sources located in the area of the Irkutsk-Cheremkhovo industrial hub as well as from local sources located on the coast of Southern Baikal. After the closure of BPPM, the substantial source of pollutants in the atmosphere, there is a tendency to a gradual decrease in concentrations and accumulation of chemical elements in snow cover from the southern part of the lake. Pollutants entering the water area of Southern Baikal are from 1.5 (nitrates) to 150 (Al) times lower than those in Irkutsk and Shelekhov. An exception is a lead, whose fluxes in the area of Southern Baikal and industrial centres are close.

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