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Distribution and role of fluorine in the aquatic ecosystem (mineral springs, groundwater, tributaries, Baikal water, and the Angara water source) of Lake Baikal, Russia

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A B S T R A C T

Several conjugate components represent the aquatic ecosystem of Lake Baikal: Baikal water (surface and deep water), groundwater from boreholes, water of numerous Baikal tributaries, cold and hot mineral springs around Lake Baikal, and the Angara River, the only runoff reflecting all this aquatic diversity. River waters in the Baikal region are known to be deficient in some vital elements, including fluorine. This article discusses the features of the fluorine distribution in the water from the conjugate components of the Baikal ecosystem. Fluorine ion concentrations in the water of the Baikal ecosystem was determined using the potentiometric method. The study represents the monitoring that was carried out between 1997 and 2022 years. We determine likely causes of high and low fluorine concentrations in the water from different components, propose and substantiate the fluorine sources, geological and geochemical model of its influx and distribution features in the water of the Baikal ecosystem.

1. Introduction

Lake Baikal is the only open water body in Russia containing clean fresh water throughout the full depth (to 1642 m). Oxygen concentrations in Baikal water reach 8–9 mg/L (at large depths) to 12–18 mg/L on the surface of the lake, making the water pleasant in taste. Close concentrations of major ions, as well as low concentrations of nutrients and organic matter, are the main features of the ionic composition of Baikal water. It is low mineralized (90–100 mg/L on average), has a stable but time-varying ionic and trace element composition with an obvious cyclicity, contains a small amount of impurities, and is in demand not only in Russia but also in other countries (Grachev MA, 2002; Domysheva VM et al., 2019; Grebenshchkova VI et al., 2021; Grebenshchikova VI and Kuzmin MI, 2022).

Lake Baikal receives water from numerous tributaries, the chemical composition of which is often significantly different from Baikal water. At the same time, not only mixing of all waters occurs in Lake Baikal but also some processes that substantially change the initial chemical composition of water from tributaries already in the littoral zone of the lake due to various currents and self-purification ability.

The ionic composition of deep and surface water in Lake Baikal varies insignificantly and does not depend on the sampling site, despite the substantial length of the lake (over 2000 km) and the varying depth in three different basins. Some researchers (Rossolimo L, 1966; Shimaraev MN et al., 2012; Shimaraev MN and Troitskaya ES, 2018) explain this to be a result of intensive mixing (upwelling/downwelling, counterclockwise movement of water along the shores, cyclic flow in three basins of the lake, etc.) and inflow of deep (juvenile) water during seismic and geodynamic movements in the Baikal Rift Zone (Didenkov YuN et al., 2006; Novopashina AV and Kuz'mina EA, 2019).

Several spatially conjugate components represent the aquatic ecosystem of Lake Baikal: Baikal water (surface and deep), groundwater from boreholes located on Olkhon Island and in the coastal part of the lake, water from a large number of tributaries (over 360), numerous cold and hot mineral springs around Lake Baikal, as well as at a distance of it, in the Baikal Rift Zone, and the Angara River, the only runoff of Lake Baikal, that reflects all this aquatic diversity. Flora and

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fauna of Lake Baikal are unique and mostly endemic. Lake Baikal is a vast and exceptional source of drinking water that can supply people with water for a long time.

Most of the area in the Baikal region belongs to the biogeochemical province with F deficiency in the surface water (Lomonosov IS, 1974; Lomonosov IS et al., 2011). Within the south of the Baikal region and Transbaikalia, the average concentration of F in natural waters is 0.2 mg/L (Fig. 1) (Grebenshchikova VI et al., 2008). The authors have previously explained the elevated fluorine concentrations (more than 1 mg/L) in the water of the Angara River and its tributaries near the cities of Shelekhov and Bratsk (Grebenshchikova VI et al., 2021). This was due to anthropogenic factor, i.e. the impact of aluminum production plants operating here). Moreover, the increase in the fluorine concentrations was simultaneously recorded in soil, snow as well as in organs and tissues of people living near the aluminum plants.

The climate and wind direction in the Baikal region are also important. Wind direction from aluminum plants (Fig. 1) often occurs along the Angara valley towards Lake Baikal. Therefore, snow from Lake Baikal and, hence, Baikal water show a slight increase in the fluorine concentrations during the spring (Grebenshchikova VI et al., 2021).

Fluorine in natural water is a biogenic element that is important for human health and biota. Various diseases reflect an excess or deficiency of F in water and, thereby, in living organisms (Zhmakin IA et al, 2020; Liu RP et al., 2021, 2022; Efimova NV et al., 2022). The optimal amount of fluorine in drinking water prevents dental caries, improves the functioning of the circulatory system, provides easier toleration of viral diseases, etc. Excess fluorine jeopardizes human health, causing dental fluorosis, disrupting the functioning of the thyroid, negatively affecting human brain activity, etc. The average concentration of F in river waters of the world is 0.09 mg/L (Dobrovolsky VV, 1983). Fluorine concentration in medicinal waters is 15.0 mg/L, and in medical table waters–10.0 mg/L (GOST 13273-88). The maximum permissible concentration (MPC) for drinking waters ranges from 0.7 mg/L to 1.5 mg/L (Kontrol', 1998;

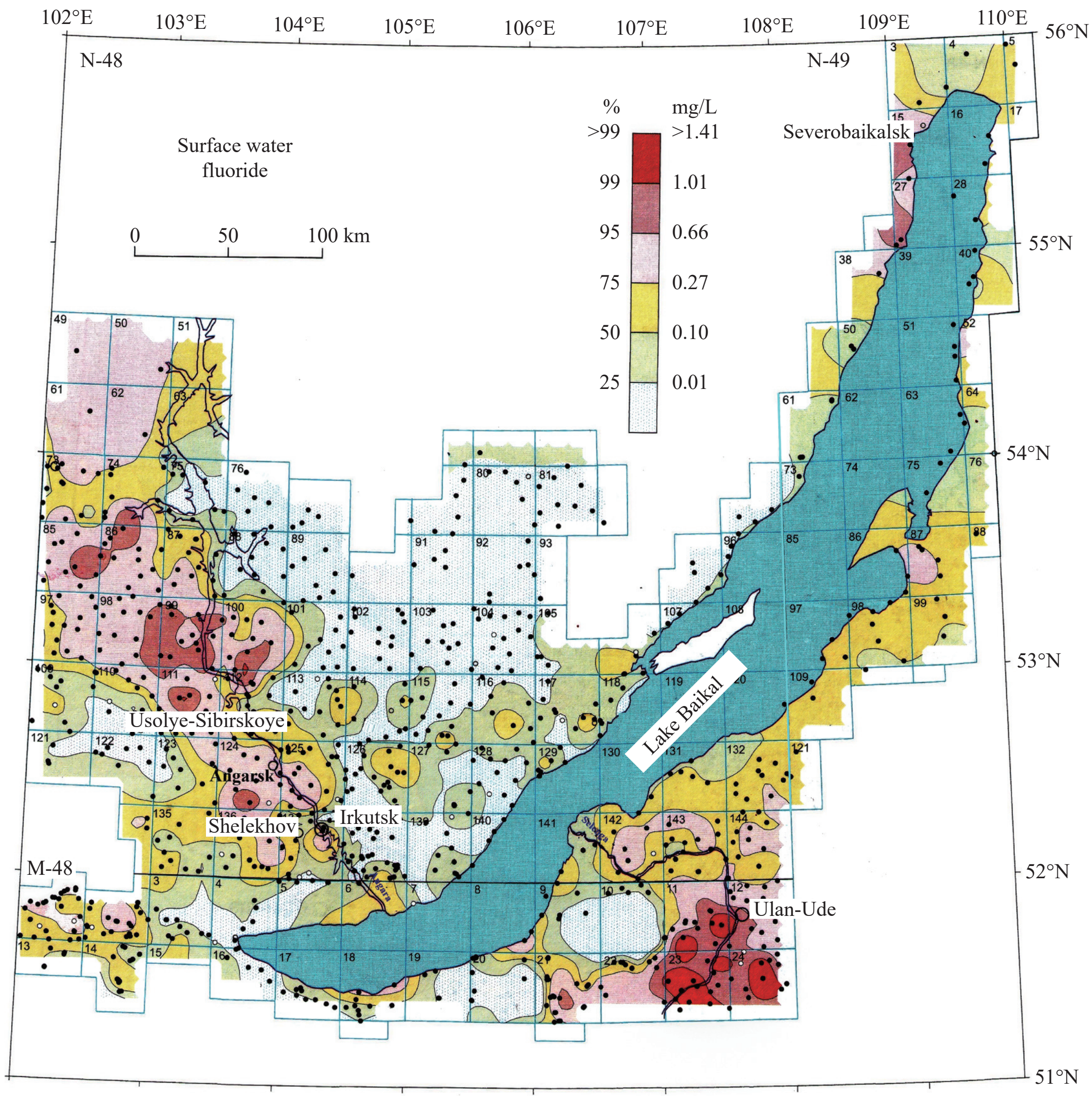

Fig. 1. Distribution of fluorine concentrations (mg/L) in the surface waters of the Baikal region (after Grebenshchikova VI et al., 2008).

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This study aims to compare and explain likely causes of significant differences in the distribution of fluorine in the waters of some conjugate components of the Baikal ecosystem: in mineral springs around Lake Baikal and at a distance from it, in boreholes of the coastal zone of Lake Baikal and on Olkhon Island, in the surface and deep (to 1640 m) water of Lake Baikal, in estuarine waters of the large Baikal tributaries and its single runoff, the Angara River.

To compare and identify the causes of the differences in the fluorine concentrations determined in water from the conjugate components of the Baikal ecosystem is an important fundamental task. Previously, the authors have identified such differences mainly by comparing the water from the Angara source and Lake Baikal (Grebenshchikova VI et al., 2021).

2. Geological setting

Lake Baikal is located in the Baikal Rift Zone that is highly seismically active (Logatchev NA, 1984, 2003; Lukhnev AV et al., 2013; Novopashina AV and Sankov VA, 2018; Radziminovich YB et al., 2020; Zorin YA et al., 2003; Novopashina AV and Lukhneva OF, 2021) and is distinguished by the shallow occurrence of the upper asthenosphere boundary, thinning of the Earth’s crust (down to 35 km in some places) (Zorin YA et all., 2003; Turutanov EK, 2018) and, therefore, elevated heat flux (Sherman SI et al., 1992; Lysak SV, 2002; Klyuchevskii AV et al., 2021).

Based on the geological structure of the area in the Baikal region, two parts can be distinguished: Western part that includes the south of the Siberian Platform (Southern Baikal region) and eastern part represented by mountain structures surrounding Lake Baikal on the eastern side (Transbaikalia) (Figs. 1, 2).

The cover of the Siberian Platform in the south of the Baikal Region consists of Phanerozoic saliferous terrigenous sediments that lack fluorine mineralization. Here, surface waters are depleted in fluorine (Fig. 1). At the same time, fluorine concentrations are high in the Angara River and its tributaries due to anthropogenic impact of the aluminum production in such cities as Shelekhov, Bratsk and Zima located on the shores of the Angara River (Figs. 1, 3).

The south of Transbaikalia is characterized by an intensive development of rare-metal granitoids with high fluorine concentrations and the presence of fluorite mineralization. Fluorine concentrations in the surface waters correspond to MPC (0.7–1.5 mg/L), but more often they are below these values, accounting for 0.2–0.3 mg/L (Grebenshchikova VI et al., 2008; Noskov DA, 2011). The huge Angara-Vitim batholith composed of Paleozoic granitoids and monzonites comes to the surface in the northeast and east of the Baikal Rift Zone (Fig. 2).

3. Water sampling and analysis methodology

Several conjugate components represent the aquatic ecosystem of Lake Baikal: Baikal water (surface and deep water), groundwater from boreholes, water from numerous tributaries of Lake Baikal, cold and hot mineral springs around Lake Baikal, and the Angara River, the only runoff reflecting all this aquatic diversity (Fig. 3).

The long-term annual (and monthly) monitoring of the composition of the water from the Angara source (from 1997 to 2022), as well as analyses of water samples from mineral springs, estuaries of tributaries, boreholes, and Lake Baikal, which were carried out in different years, involving chemical analysis for a wide range of elements, including fluorine, facilitated the achievement of our goal. Previously, water from boreholes was monitored in the Listvyanka settlement (Alekseev SV et al., 2018; Alekseeva LP et al., 2023).

Fluorine ion concentrations in the water of the conjugate components of the Baikal ecosystem were determined by the potentiometric method at the Centre of Isotopic and Geochemical Research in IGC SB RAS (Skuzovatov SYu et al., 2022; Table 1).

4. Results of the analysis of natural water in the conjugate components of the Baikal ecosystem and their discussion

4.1. Mineral springs

In the Baikal Rift Zone around Lake Baikal and at a distance from it, there is a large number of both natural outlets of mineral springs with different chemical composition and those uncovered by boreholes. This has always aroused the interest of many researchers and, thereby, contributed to many publications discussing their origin, chemical composition, different water temperatures, and balneological properties of various types of mineral waters (Lomonosov IS, 1974; Zamana LV, 2000; Speizer GM, 2010; Plyusnin AM et al., 2013, 2008; Sklyarov EV et al., 2015; Kuz’mina EA and Novopashina AV, 2018; Novopashina AV and Kuz’mina EA, 2017, 2019). Residents of the Baikal region and Russia actively use mineral waters for the treatment of different diseases because they contain a various chemical elements necessary for health. Sanatoriums and tourist bases have been built near many mineral springs in the Baikal region. There are also some wildlife resorts (Fig. 3).

«*Wildlife*» tourism is widespread on the Baikal shores in different seasons, even in the winter. Such tourism often has a negative impact on the lake and causes many problems for the authorities due to the pollution of the littoral zone of Lake Baikal and coastal areas. Recently, Victor I. Danilov-Daniliyan, editor-in-chief of the international peer-reviewed journal «*Water Resources*» has proposed charging a monetary fee to “wild” tourists for cleaning the coastal places they visit.

At the same time, all state resorts and sanatoriums in the Baikal aquatic ecosystem undergo official inspection, have medical staff and specific medical recommendations for the treatment and health care of patients.

The available information about the fluorine ion concentrations in 14 mineral springs (32 detections of fluorine in different seasons) indicated variations from 23 mg/L to 2 mg/L, to 40 mg/L (according to Lomonosov IS, 1974) and 0.1

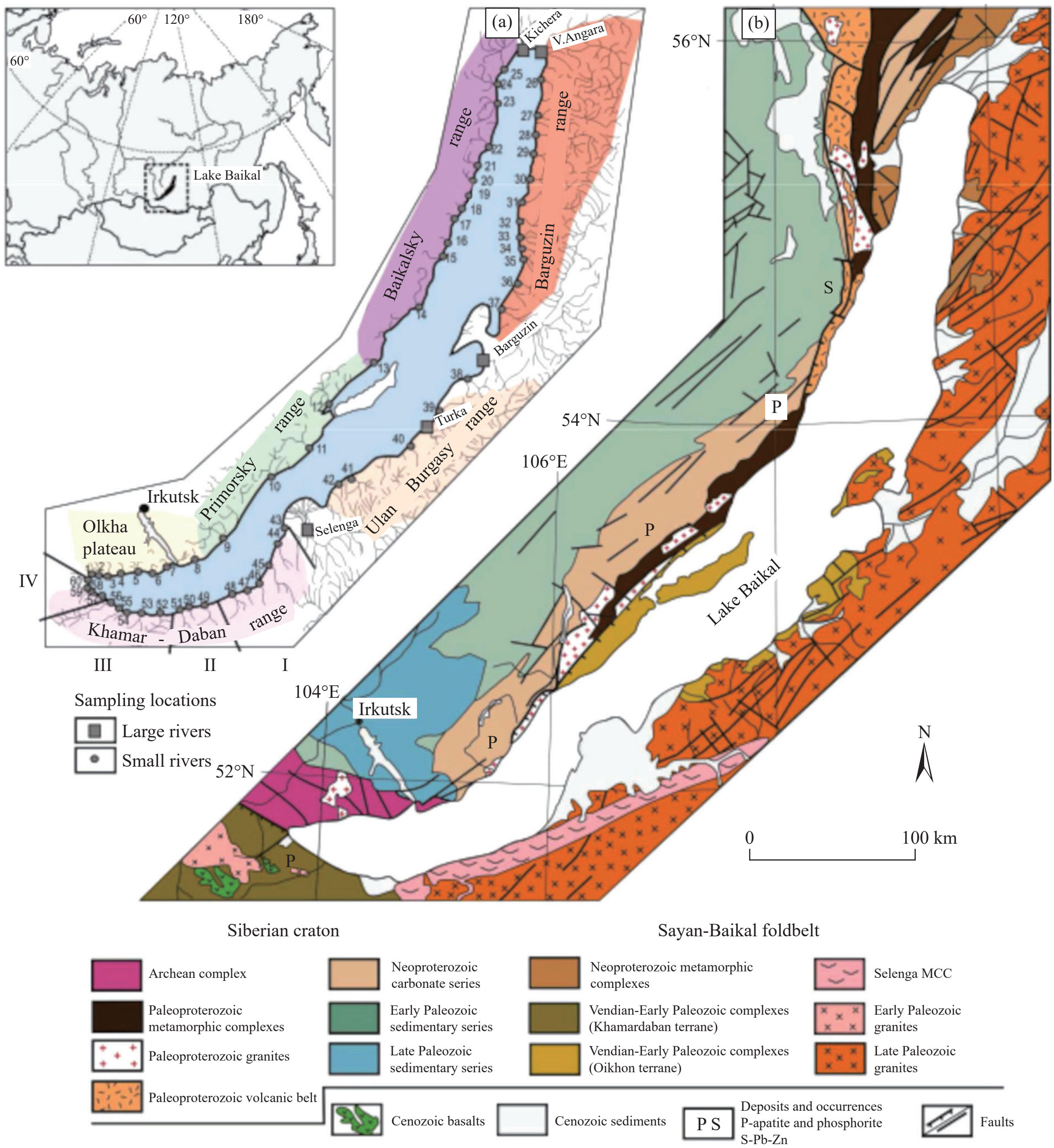

Fig. 2. Schematic map of the geological structure of the Baikal aquatic ecosystem (after Sklyarova OA, 2017).

mg/L at a distance from Lake Baikal (cold springs in the Khudyakovo and Nikola settlements, etc.) (Fig. 4, Table 1).

Elevated (sometimes by a factor of 100 or more) F^- concentrations in the water with relatively average values for the region, which amount to 0.2 mg/L (Grebenshchikova VI et al., 2008), were characteristic mainly of hot mineral springs such as Kotelnikovsky, Zmeiny, Kulinye bogs and others. Springs with lower F^- concentrations (2 to 3.5 mg/L) are Goryachinsk, Frolikha, Khakusy and others. Elevated F^- concentrations in hot mineral springs testified to their relationship with deeper fluid and hydrothermal systems of the Baikal Rift Zone (Lomonosov IS., 1974). In this case, the mantle (asthenospheric) supply of fluorine, sulfur, chlorine, and other elements was assumed. Some researchers (Zamana LV, 2000; Plyusnin AM et al., 2013, 2020; Shvartsev SL et al., 2007), who admitted deep entry of elements, believed that their high concentrations, in particular fluorine concentration, can also be due to its additional entry from host granitoid rocks with fluorine-bearing minerals (fluorite, beryl, lepidolite, sericite, etc.) during the interaction of hydrothermal fluids with aluminosilicates. This is rather logical and was demonstrated on the example of some tributaries of Lake Baikal (Plyusnin AM et al., 2008, 2013, 2020; Pavlov SK and Chudnenko KV, 2013; Zamana LV, 2000).

Sklyarov EV et al. (2015) suggested that some thermal springs around Lake Baikal might be “natural pollutants” of Baikal water because ore elements were often found in mineral springs. However, due to specific currents (cyclic in

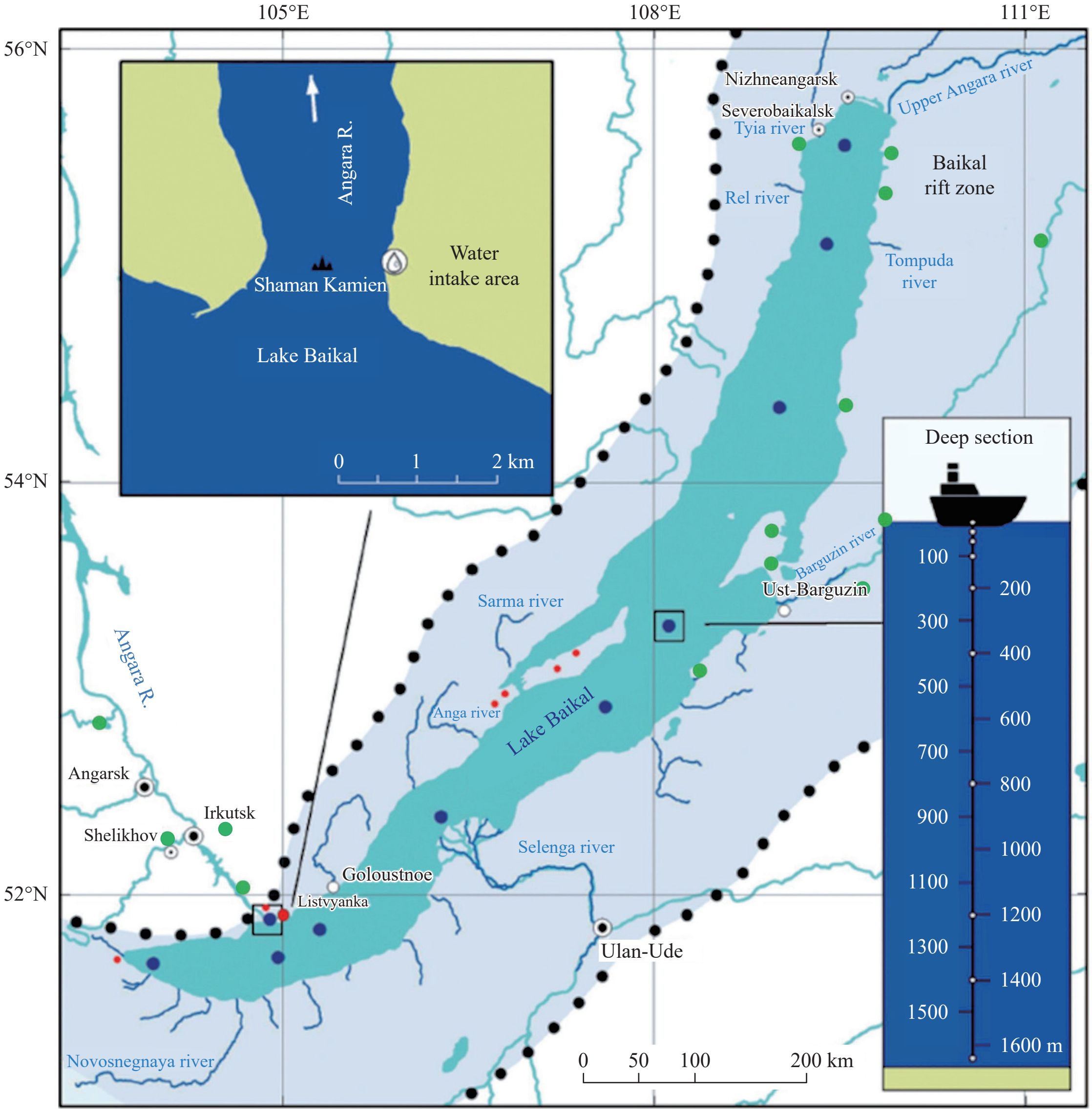

Fig. 3. Scheme of water sampling from the conjugate components of the Baikal ecosystem (blue dots mark Baikal water, squares with dots–sampling sites of deep water and water from the Angara source, red dots–water from boreholes, green circle–water from mineral springs).

Table 1. F^- concentrations (mg/L) in the water from the conjugate components of the Baikal ecosystem.

Concentration/component	Mineral springs	Groundwater (boreholes)	Tributaries	Lake Baikal (surface and deep water)	Source of the Angara River
Maximum	23.0	1.13	0.65	0.40	0.30
Minimum	0.1	0.07	0.02	0.16	0.11
Average	11.0	0.35	0.17	0.22	0.20
Median	12.0	0.30	0.13	0.22	0.20
Number of samples	32	23	214	118	488

three basins of Lake Baikal, counterclockwise along the shores of Lake Baikal and other features of water movement), as well as the deposition of elements on geochemical barriers in the littoral zones of the lake and rapid mixing of water in Lake Baikal, these pollutants do not change significantly the concentrations of elements in Baikal water, including fluorine. Thus, its low concentrations in Baikal water, and the water of its only runoff, the Angara River, clearly reflect this (Fig. 4).

4.2. Groundwater (boreholes).

The authors analyzed groundwater from 17 boreholes to determine the fluorine concentrations in the waters around Lake Baikal (Listvyanka, Nikola, Olkha, and other settlements) and on Olkhon Island. From some boreholes, groundwater was sampled twice in different seasons, and the F concentrations were close in the water (Table 1). Water from seven boreholes was analyzed in the Listvyanka settlement (southwestern coast of Lake Baikal). There was no correlation between fluorine concentration in the water from the boreholes and their depth. The water from the boreholes had lower fluorine concentrations than the water from hot mineral springs but sometimes-reached normal MPCs, i.e.

0.75 mg/L to 1.5 mg/L (Olkhon Island, Elantsy settlement, Nikola settlement, Olkha in the suburbs of Irkutsk, etc.). Such water is obviously good for residents due to the lack of fluorine in the Baikal region. Overall, we carried out 23 analyses to determine F^- concentrations in boreholes and springs.

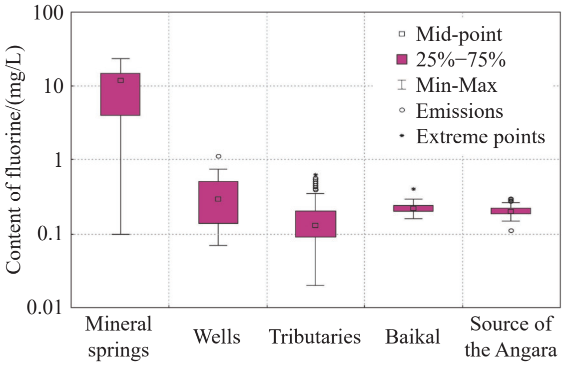

Fig. 4. Distribution diagram of F^- concentrations in the conjugate aquatic components of the Baikal ecosystem (mg/L).

Elevated fluorine concentrations in the groundwater of the Baikal region were owing to its elevated concentrations in Paleoproterozoic granitoid and subalkaline rocks common on the west coast of Lake Baikal (near the Elantsy settlements, on Olkhon Island and at other sites) (Baicalogy, 2012). High fluorine level is also because of the occurrence depth of aquifer, like in the Olkha settlement (depth 310 m) where table mineral water “Irkutskaya” with the human-beneficial fluorine concentration (>1 mg/L) is extracted (Alieva VI and Zagorul'ko NA, 2013) (Fig. 4). The genetic relationship of fluorine with the host rocks drained by deep water can be traced by its relatively high concentration in the water from boreholes.

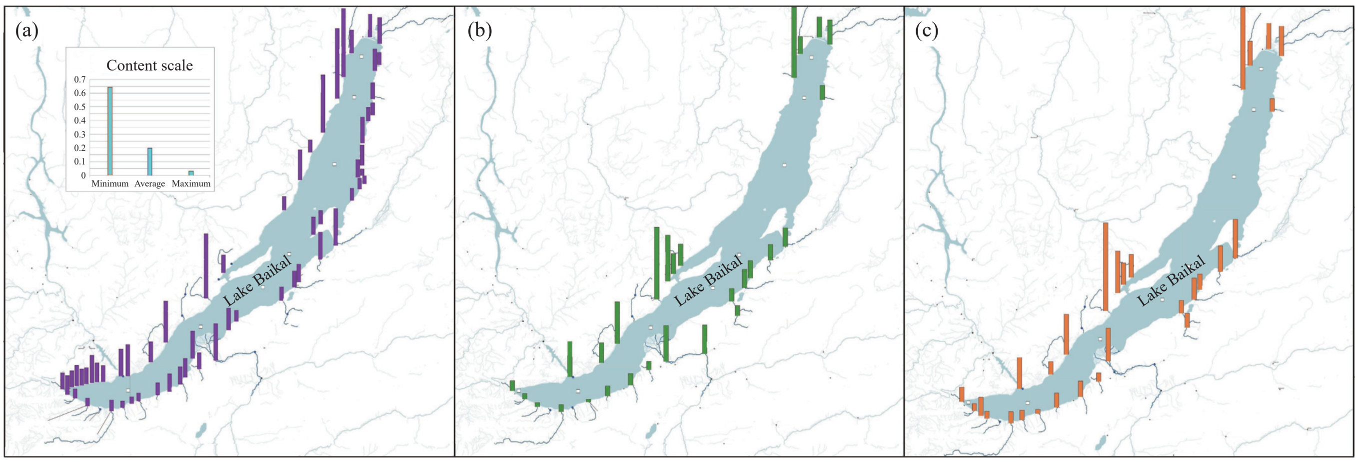

Fig. 5. Distribution of fluorine ion concentrations in the water from the estuaries of the Baikal tributaries: Summer of 2007, spring of 2019 and autumn of 2019 (mg/L).

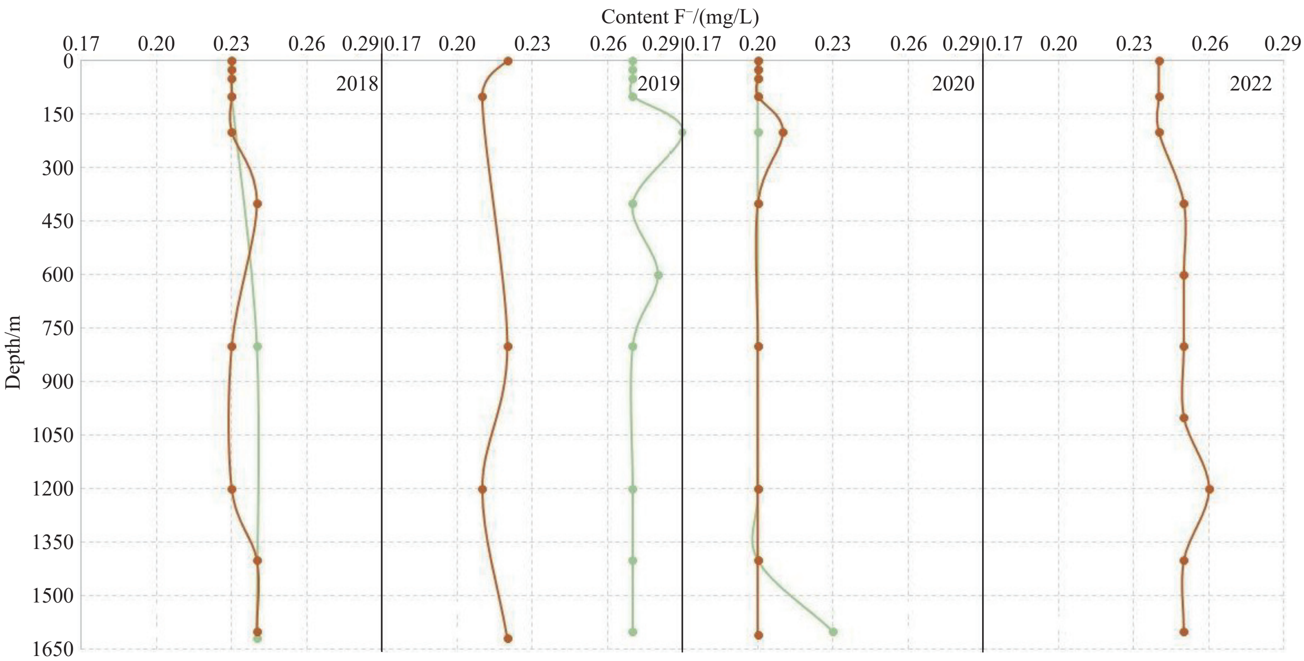

Fig. 6. Distribution of F^- concentrations (mg/L) in the surface and deep water of Lake Baikal in 2018 to 2020 and 2022 (green lines mark spring and brown lines–autumn).

4.3. Tributaries of Lake Baikal.

The chemical composition of water sampled from 30 to 35 estuaries of the tributaries around Lake Baikal was studied between 2007 and 2022 in different seasons. Water in tributaries surrounding Lake Baikal significantly differed in the fluorine ion concentrations due to the influence of drained bedrocks with different composition. According to the geological map of Lake Baikal (Baicalogy, 2012; Sklyarova OA et al., 2017), high F^- concentrations (0.3 mg/L-0.65 mg/L) were recorded at the estuaries of large tributaries that drain granitoid rocks of different ages on the eastern (huge the Angara-Vitim granitoid batholith) and the western side of Lake Baikal (Paleoproterozoic granites): the Rel, the Anga, the Upper Angara, the Buguldeika, the Kuchelga, the Ust-Barguzin, and some other rivers.

Most tributaries in the southeastern part of Lake Baikal (the Snezhnaya, the Khara-Murin, the Slyudyanka, and other rivers), always showed low F^- concentrations in different seasons (Fig. 5), 0.05 mg/L to 0.1 mg/L. Here, the basic composition of the Khamar-Daban mountain range with low fluorine concentrations represents host rocks.

In the southwestern part of Lake Baikal, numerous tributaries (the Angasolka, the Marituy, the Polovinka, the Shumikha, and other rivers) drain Archean metamorphic rocks (marbles, quartzites, crystalline schists, etc.). The fluorine ion concentrations were two times higher at the estuaries of these tributaries than in the southeastern tributaries (up to 0.2 mg/L). They were close to the values for the water from Lake Baikal and the Angara source.

At the source of the Selenga River, the F^- concentration sometimes reached 0.4 mg/L in different seasons, but anthropogenic factor can also influence here due to the industrial facilities in its basin.

4.4. Baikal water.

From 2011 to 2022, 118 water analyses were carried out to determine F^- concentrations. The fluorine ion concentrations were very close in deep and surface water and did not exceed 0.2 mg/L-0.3 mg/L. Within 2018 to 2022, there were no significant changes in the fluorine concentrations from the surface of the lake to a depth of 1640 m (Fig. 6). There were also no differences in the fluorine concentrations in different seasons of the year (spring and autumn). The maximum F^- concentration (0.4 mg/L to 0.54 mg/L) was recorded only two times, in the spring and autumn of 2020, in the surface water from the center of Lake Baikal, opposite the estuary of the Selenga River, in which the fluorine concentrations reached 0.4 mg/L (Fig. 4). This can be explained only by a rapid current during a sharp change in weather (storm, hurricane, strong wind, etc.) at the estuary of the Selenga River and at Lake Baikal or by a one-time increase in the fluorine concentrations in the water of the Selenga due to the anthropogenic impact of industrial enterprises in its basin. The influence of frequent seismic movements in 2020 in the Baikal region was possible.

4.5. Water from the Angara source.

The monthly monitoring sampling at the site of the Angara source yielded results of the analysis for fluorine ion based on 488 water samples taken from 1998 to 2022 (Figs. 4, 7, Table 1). The F^- concentrations in the water from the source were rather low (down to 0.11 mg/L); the maximum rarely reached 0.3 mg/L, and the average and median were the same (0.2 mg/L). In other words, the F^- concentration was five to ten times lower than MPC for drinking water (0.7 mg/L to 1.5 mg/L). During the study period, relatively high F^- concentrations in the water of the source were recorded from 1997 to 2003 (Fig. 7). Then, since 2007, there was an obvious decrease in the fluorine concentrations. Between 2017 and 2022, the average annual fluorine ion concentrations in the water of the Angara source increased insignificantly to 0.22-0.23 mg/L (Fig. 7). This may be due to an increase in the tourist pressure during this period in the southern basin of Lake Baikal and at the Angara source (Suturin AN et al., 2016). In recent years (2020 to 2022), fluorine concentrations have slightly increased at the source of the Angara River. This can be due to an increase in the number of tourists visiting Lake Baikal during the pandemic.

5. Discussion

High fluorine concentrations in thermal springs of the Baikal region are still the subject of discussion among researchers. Previously, Lomonosov IS (1974) stated that solutions of magmatic genesis (juvenile waters) were the source of this element in thermal springs. However, currently, many researchers consider host rocks a fluorine source. At the same time, the mechanism of fluorine mobilization from rocks is understood differently. Some researchers associate it with high concentrations of this element in the host rocks, particularly in micas (Plyusnin AM et al., 2008), based on the equilibrium-nonequilibrium state of the water-rock system, the time of interaction of water with rocks and the nature of the geochemical environment (Shvartsev SL et al., 2015, 2017).

In recent years, new patterns of relationship between the chemical composition and temperature of thermal waters with tectonic and seismic processes have been revealed for the Baikal region (Kuzmina EA, 2011, 2022; Kuz'mina EA and

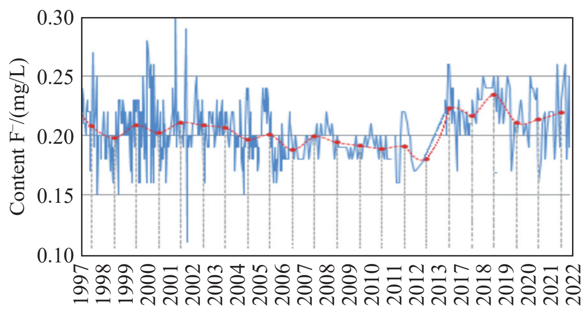

Fig. 7. Monthly (blue) and average annual concentrations (red) of fluorine ion in the water of the Angara source from 1998 to 2022 (mg/L).

Novopashina AV, 2018). The number of thermal springs grew with an increase in the degree of the Earth's crust fragmentation by active faults, and the maximum and average temperature in the springs decreased due to the possible dilution of thermal water in more disturbed environment by low-temperature waters of near-surface aquifers.

The data on the distribution of fluorine in water components of the Baikal ecosystem allowed the authors to present a geological and geochemical model of the likely influx of fluorine to thermal sources from high-temperature juvenile water-gas fluids that were probably present in the conductive layer of the Earth's crust in the Baikal Rift Zone at depths of 7 km to 27 km under depressions and 15 km to 35 km under uplifts (Fig. 8). It was assumed that fluorine can diffuse and penetrate along active faults through the layers of the dry upper mantle and lower Earth's crust from the asthenospheric melt at depths of 78 km to 130 km (Berdichevsky MN et al., 1999; Nielsen Ch and Thybo H, 2009; Seminsky KZh and Tugarina MA, 2011; Ten Brink US and Taylor MH, 2002). Active faults can also provide transit of fluorine to the surface from the conductive layer of the middle crust, leading to the elevated concentrations of many chemical elements, including fluorine, in modern thermal springs (Letnikov FA 2006; Lomonosov IS et al., 2011; Novopashina AV and Kuz'mina EA, 2019).

The data on the F distribution in the water of the Baikal ecosystem indicates its regular development. Fluorine is found everywhere in water, but it is distributed differently in

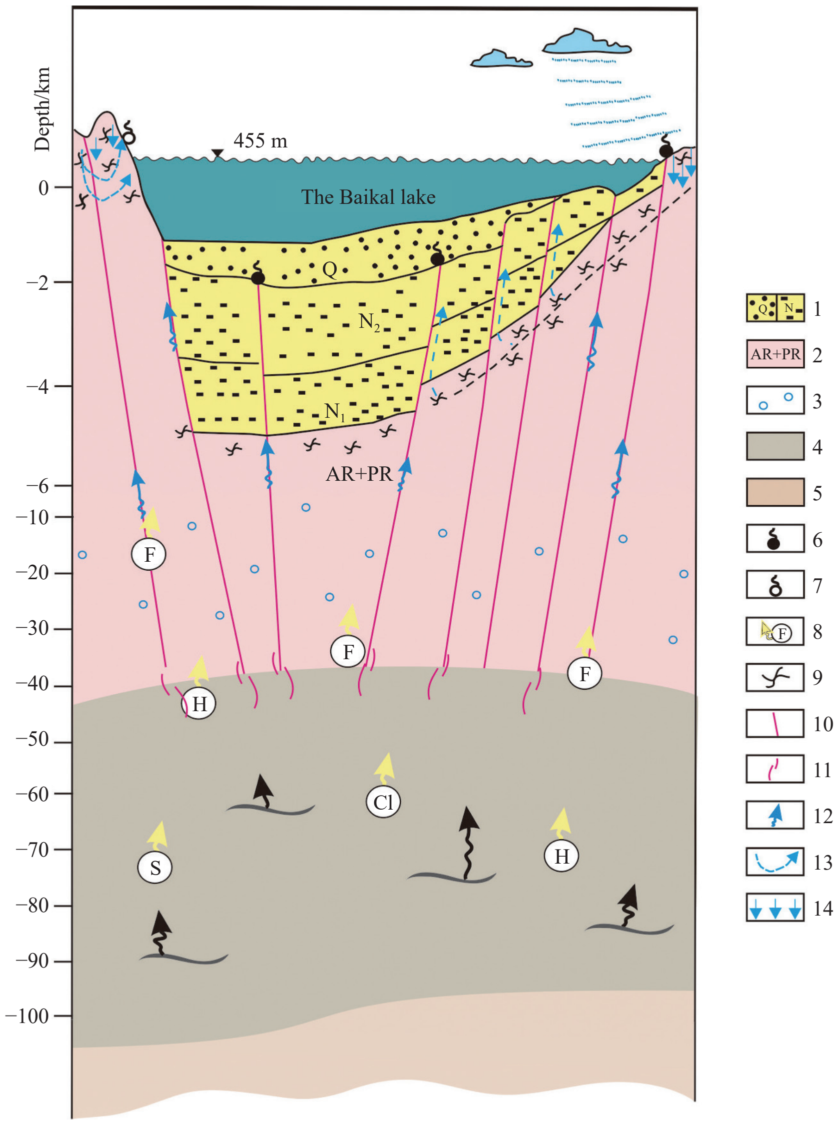

Fig. 8. A generalized scheme of geological and geochemical model of fluorine influx to the water of the Baikal region (after Lomonosov IS and Pokatilov YuG, 1986; Didenkov YuN et al., 2006) with the additions: 1–Cenozoic deposits (Q–polygenetic facies of the Quaternary molasse formation; N2–coarse-grained clastic molasse formation of the Upper Neogene; N1–fine-grained molassoid formation of the Lower Neogene); 2–Earth's crust (magmatic and metamorphic formations of the Archean-Proterozoic age, AR+PR); 3–conductive layer according magnetotelluric sounding data (Pospeev AV, 2012); 4–upper mantle roof according velocity structure (Nielsen Ch and Thybo H, 2009); 5–asthenosphere according magnetotelluric sounding data (Berdichevsky MN et al., 1999); 6–modern thermal springs; 7–natural cold water outlets; 8–chemical elements in the gas phase; 9–fractures in rocks; 10–active faults reaching the Moho depth (Seminsk KZ and Tugarina MA, 2011); 11–melatinization zone (Letnikov FA, 2006); 12–direction of supposed fluorine movement; 13–direction of meteoric water movement; 14–precipitation.

different components of Lake Baikal. In the water from Lake Baikal, the Angara source and the Baikal region (Fig. 1), the fluorine concentration is below the MPC for drinking water. In the waters of numerous tributaries and groundwater of Lake Baikal, its concentrations increase to the MPC level. Moreover, the maximum concentrations of F ion are typical of only numerous thermal springs around Lake Baikal, which residents of the Baikal region actively use for medicinal purposes. Nature compensates and, perhaps, correctly redistributes such biogenic element as fluorine necessary for humans in the Baikal region.

6. Conclusions

An analysis of the obtained geological and geochemical information about the distribution of fluorine concentrations in the water of the conjugate components of the Baikal ecosystem draws the following conclusions:

(i) The water in the rivers of the Baikal region is deficient in fluorine due to the geological structure and originally low fluorine concentrations in rocks and soil. However, aluminum production plants operating more than 60 years in the region demonstrate a significant input of fluorine and its negative impact on the surrounding soil, snow and river water as well as on people living near the plants.

(ii) Significant differences in the fluorine concentrations from different aquatic components of the Baikal ecosystem indicate the influence of its confinement to the Baikal Rift Zone where earthquakes and geodynamic movements often occur, accompanying by insignificant changes in the fluorine concentrations in Lake Baikal and, hence, in the Angara source. At the same time, the activity of thermal springs surrounding it continues.

(iii) Climate change and continental climate (from +35°C to –40°C) in the Baikal region, frequent warming and drought (2000 to 2014), as well as a decrease in the industrial pressure in the region during these years, led to a slight increase in fluorine in the Angara source. Cooling between 2017 and 2020 was replaced by an increase in the water level in Lake Baikal, flooding on the tributaries and the Angara River and high tourist pressure on Lake Baikal due to the pandemic and other events that caused an increase in the fluorine concentrations in the Angara source.

(iv) Elevated fluorine concentrations in the water from boreholes on Olkhon Island and some coastal areas of Lake Baikal, which were close to those necessary for human health, indicate the impact of drained granitoid rocks with relatively high fluorine concentrations on groundwater.

(v) Under favorable structural and tectonic conditions (zones of deep faults), hydrothermal fluid solutions from deep layers of the Earth (2–5 km) can deliver juvenile solutions to the surface, which are enriched in many elements, including ore from the water-containing layers of the Earth.

(vi) Some factors ensure the stability of Baikal water and its safety: the possible entry of deep elements into Baikal water and its renewal, deposition of toxic elements at the estuaries of numerous tributaries on geochemical barriers, etc.

(vii) To keep the water of the Baikal ecosystem clean, which is of the global importance (protected by UNESCO), it is necessary to significantly improve the integrated tourism recreation and socioeconomic development around Lake Baikal.

CRediT authorship contribution statement

Conceptualization: Valentina Grebenshchikova, Mikhail Kuzmin, Anna Novopashina, Elena Kuz'mina; Methodology: Valentina Grebenshchikova, Mikhail Kuzmin; Validation and Data curation: Valentina Grebenshchikova, Mikhail Kuzmin, Anna Novopashina, Elena Kuz'mina; Original draft preparation: Valentina Grebenshchikova; Writing-review and editing: Valentina Grebenshchikova, Mikhail Kuzmin, Anna Novopashina, Elena Kuz'mina; All authors have read and agreed to the published version of the manuscript.

Declaration of competing Interest

The authors declare no conflicts of interest.

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References

Alekseev SV, Alekseeva LP, Sholokhov PA, Orgilyanov AI, Kononov AM. 2018. The groundwater and surface water quality in the area of the settlement of Listvyanka. Geography And Natural Resources, 4, 105–114 (in Russian). doi: 10.21782/GiPR0206-1619-2018-4(105-114).

Alexeeva LP, Alexeev SV, Sholokhov PA, Kononov AM. 2023. Monitoring of Groundwater Quality in Listvyanka Settlement (Southwest Coast of Lake Baikal). Geodynamics & Tectonophysics, 14(2), 1–13. doi: 10.5800/GT-2023-14-2-0697.

Alieva VI, Zagorul'ko NA. 2013. Vliyanie prirodnyh i tekhnogennyh faktorov na gidrohimicheskij sostav rek promyshlennoj zony g. Irkutska. Voda: himiya i ekologiya, 6, 16–21 (in Russian).

Baicalogy: Text-book for students of natural scientific specialties. 2012. Book 1. Novosibirsk, Nauka (in Russian).

Berdichevsky MN, Vanyan LL, Koshurnikov AV. 1999. Magnetotelluric sounding in the Baikal rift zone. Izvestiya, Physics of the Solid Earth, 35(10), 793–814.

Didenkov YuN, Bychinskii VA, Lomonosov IS. 2006. The possible existence of an endogenous source of fresh waters in rift settings. Russian Geology and Geophysics, 10, 1098–1102.

Dobrovolsky VV. 1983. Geography of trace elements. Global scattering. Moscow, Mysl (in Russian).

Domysheva VM, Sorokovikova LM, Sinyukovich VN, Onishchuk NA, Sakirko MV, Tomberg IV, Zhuchenko NA, Golobokova LP, Khodzher TV. 2019. Ionic Composition of Water in Lake Baikal, Its Tributaries, and the Angara River Source during the Modern Period. Russian Meteorology and Hydrology, 44(10), 687–694. doi: 10.3103/s1068373919100078.

Efimova NV, Lisetskaya LG, Savchenkov MF. 2022. Fluorine excretion in children at various levels of exposure to emissions from aluminum production. Ekologiya cheloveka (Human Ecology), 29(8), 599–607. doi: 10.17816/humeco106008.

GOST 13273-88. "Vody mineral'nye pit'evye lechebnye i lechebno-stolovye" (in Russian).

Grachev MA. 2002. O sovremennom sostoyanii ekologicheskoj sistemy ozera Bajkal. Novosibirsk, Izd-vo SO RAN (in Russian).

Grebenshchikova VI, Kuzmin MI. 2022. The Cyclic-Wave Character of the Distribution of Chemical Elements in the Water of the Source of the Angara River (Runoff of Lake Baikal). Doklady Earth Sciences, 505, 578–585. doi: 10.1134/S1028334X22080086.

Grebenshchikova VI, Kuzmin MI, Rukavishnikov VS, Efimova NV, Donskikh IV, Doroshkov AA. 2021. Chemical contamination of soil on urban territories with aluminum production in the Baikal region, Russia. Air, Soil and Water Research, 14, 1–11. doi: 10.1177/11786221211004114.

Grebenshchikova VI, Lustenberg EE, Kitaev NA, Lomonosov IS. 2008. Geohimiya okruzhayushchej sredy Pribajkal'ya (Bajkal'skij geoekologicheskij poligon). Novosibirsk, Akademicheskoe izd-vo «Geo» (in Russian).

Grebenshchkova VI, Kuzmin MI, Suslova MY. 2021. Long-term cyclicity of trace element in the Baikal aquatic ecosystem (Russia). Environmental Monitoring and Assessment, 193(5), 260. doi: 10.1007/s10661-021-09021-1.

Klyuchevskii AV, Grebenshchikova VI, Kuz'min MI, Dem'yanovich VI, Klyuchevskaya AA. 2021. The relationship between powerful geodynamic impacts and an increase in the mercury content of the water of the Angara river source (Baikal rift zone). Russian Geology and Geophysics, 62(2), 239–254. doi: 10.2113/RGG20194139.

Kontrol' himicheskih i biologicheskih parametrov okruzhayushchej sredy. 1998. Pod redakciej Isaeva L. K. SPB. Ekologo-analiticheskij informacionnyj centr «Soyuz» in Russian.

Kuz'mina EA, Novopashina AV. 2018. Groundwater outflows and fault density spatial relation in the Baikal rift system (Russia). Acque Sotterranee - Italian Journal of Groundwater, 7(1), 19–27. doi: 10.7343/as-2018-317.

Kuzmina EA. 2011. Relationship between nitrogen thermal waters and fault tectonics of the Barguzino-Bauntovskaya branch of the basins of the Baikal rift system. PhD thesis. IEC SB, RAS Irkutsk, Russia in Russian.

Kuzmina EA 2022. List of thermal waters of the northeast of the Baikal rift system (53°–56° N, 109°–114° E) and their main characteristics. ESDB repository, GC RAS, Moscow. doi: 10.2205/ESDB-RJES-data-824.

Letnikov FA 2006, Fluids in endogenic processes and problems of metallogeny. Russian Geology and Geophysics, 47(12), 1271–1281.

Liu RP, Zhu H, Liu F, Dong Y, El-Wardany RM. 2021. Current situation and human health risk assessment of fluoride enrichment in groundwater in the Loess Plateau: A case study of Dali County, Shaanxi Province, China. China Geology, 4(3), 487–497. doi: 10.31035/cg2021051.

Liu RP, Liu F, Dong Y, Jiao JG, RM El-Wardany, Zhu LFi. 2022. Microplastic contamination in lacustrine sediments in the Qinghai-Tibet Plateau: Current status and transfer mechanisms. China Geology, 5(3), 421–428. doi: 10.31035/cg2022030.

Logatchev NA. 1984. The Baikal Rift System. Episodes, 7, 38–42. doi: 10.18814/epiiugs/1984/v7i1/009.

Logatchev NA. 2003. History and geodynamics of the Baikal rift, Russian Geology and Geophysics, 5, 373–387.

Lomonosov IS, Grebenshchikova VI, Sklyarova OA, Bryukhanova NN, Noskov DA, Yanovskii LM, Didenkov YN. 2011. Toxic (mercury, berillium) and biogenic (selenium, fluorine) elements in aquatic ecosystems of Baikal Natural Territory. Water Resources, 38(2), 199–210. doi: 10.1134/s0097807811020084.

Lomonosov IS, Pokatilov YuG. 1986. Biogeochemical Assessment of Natural Waters in Environmental Components in Baikal Region. Geokhimiya tekhnogeneza (Biochemistry of Technogenesis), Novosibirsk, Nauka in Russian.

Lomonosov IS. 1974. Geohimiya i formirovanie sovremennyh gidroterm Bajkal'skoj riftovoj zony. Novosibirsk, izd-vo Nauka SO RAN in Russian.

Lukhnev AV, San'kov VA, Miroshnichenko AI, Ashurkov SV, Byzov LM, San'kov AV, Bashkuev YB, Dembelov MG, Calais E. 2013. GPS-measurements of recent crustal deformation in the junction zone of the rift segments in the central Baikal rift system. Russian Geology and Geophysics, 54(11), 1417–1426. doi: 10.1016/j.rgg.2013.10.010.

Lysak SV. 2002. Heat flow in the zones of active faults in the south of Eastern Siberia. Russian Geology and Geophysics, 8, 791–803.

Nielsen C, Thybo H. 2009. No Moho uplift below the Baikal Rift Zone: Evidence from a seismic refraction profile across southern Lake Baikal. Journal of geophysical research: Solid Earth, 114(B8), B08306. doi: 10.1029/2008JB005828.

Noskov DA. 2011. Geochemical features and conditions of the Angara-Vitim granitoid batholith formation (Eastern Cisbaikalia). PhD thesis. IGH SO, RAN Irkutsk, Russia in Russian.

Novopashina AV, Sankov VA. 2018. Migrations of released seismic energy in various geodynamic conditions. Geodynamics & Tectonophysics, 9(1), 139–163. doi: 10.5800/GT-2018-9-1-0342.

Novopashina AV, Kuz'mina EA. 2019 Influence of crustal fracturing on the thermal springs and earthquake swarms distribution in the north-east part of the Baikal rift system (Russia). Acque Sotterranee - Italian Journal of Groundwater, 8(2), 23–36. doi: 10.7343/as-2019-360.

Novopashina AV, Kuz'mina EA. 2017. Earth's Crust Faults Density and Thermal Springs in the Seismic Activity Migration Zone at the Amutsky Swarm Region. The Bulletin of Irkutsk State University». Series «Earth Sciences», 20, 81–90 (in Russian).

Novopashina AV, Lukhneva OF. 2021. The propagation velocity of seismic activity migrating along the directions of the geodynamic forces prevailing in the northeastern Baikal rift system, Russia. Annals of Geophysics, 64(4), SE436. doi: 10.4401/ag-8654.

Pavlov SK, Chudnenko KV. 2013. Formation of nitrogen-rich hot springs: Modeling physicochemical interactions in a water-granite system. Geochemistry International, 51(12), 981–993. doi: 10.1134/s0016702913120069.

Plyusnin AM, Chernyavskii MK, Posokhov VF. 2008. Formation conditions of thermal springs in the Barguzin-Baikal area: evidence from trace element and isotopic composition. Geochemistry International, 46(10), 996–1004. doi: 10.1134/S0016702908100042.

Plyusnin AM, Zamana LV, Shvartsev SL, Tokarenko OG, Chernyavskii MK. 2013. Hydrogeochemical peculiarities of the composition of nitric thermal waters in the Baikal Rift Zone. Russian Geology and Geophysics, 54(5), 495–508. doi: 10.1016/j.rgg.2013.04.002.

Plyusnin AM, Khazheeva ZI, Sanzhanova SS, Peryazeva EG, Angakhaeva NA. 2020. Sulfate mineral lakes of western Transbaikalia: formation conditions and chemical composition of waters and bottom sediments. Russian Geology and Geophysics, 61(8), 858–873. doi: 10.15372/RGG2019154.

Pospeev AV. 2012. The velocity structure of the upper mantle and regional deep thermodynamics of the Baikal rift zone. Geodynamics & Tectonophysics, 3(4), 377–383. doi: 10.5800/GT-2012-3-4-0080.

Radziminovich YB, Gileva NA, Tubanov TA, Lukhneva OF, Novopashina AV, Tcydypova LR. 2022. The December 9, 2020, Mw 5.5 Kudara earthquake (Middle Baikal, Russia): internet questionnaire hard test and macroseismic data analysis. Bulletin of Earthquake Engineering, 20(3), 1297–1324. doi: 10.1007/s10518-021-01305-8.

Rossolimo L. 1966. Baikal. Moscow, Nauka (in Russian).

SANPIN 2.4. 1116-02. Pit'evaya voda. Gigienicheskie trebovaniya k kachestvu pit'evoj vody, rasfasovannoj v emkosti. Kontrol' kachestva (in Russian).

Seminsky KZh, Tugarina MA. 2011. Results of comprehensive studies of the underground hydrosphere within the western shoulder of the Baikal rift (as exemplified by the Bayandai - Krestovsky cape site). Geodynamics & Tectonophysics, 2(2), 126–144. doi: 10.5800/GT-2011-2-2-0037.

Sherman SI, Seminsky KZh, Bornyakov SA, Adamovich AN, Lobatskaya RM, Lysak SV, Levi KG. 1992. Faulting in the Lithosphere. Extensional zones. Novosibirsk, Nauka (in Russian).

Shimaraev MN, Troitskaya ES, Blinov VV, Ivanov VG, Gnatovskii RY. 2012. Upwellings in Lake Baikal. Doklady Earth Sciences, 442(2), 272–276. doi: 10.1134/s1028334x12020183.

Shimaraev MN, Troitskaya ES. 2018. Current trends in upper water layer temperature in coastal zones of Baikal. Geography and Natural Resources, 39(4), 349–357. doi: 10.1134/S187537281804008X.

Shvartsev SL, Ryzhenko BN, Alekseev VA, Dutova EM, Kondratieva IA, Kopylova YuG, Lepokurova OE. 2007. Geological evolution and self organizing of water–rock system. V. 2. Water–rock system in conditions of a zone of active water exchange. Novosibirsk, Siberian Branch of the Russian Academy of Science Publ. house (in Russian).

Shvartsev SL, Zamana LV, Plyusnin AM, Tokarenko OG. 2015. Equilibrium of nitrogen-rich spring waters of the Baikal Rift Zone with host rock minerals as a basis for determining mechanisms of their formation. Geochemistry International, 53(8), 713–725. doi: 10.1134/S0016702915060087.

Shvartsev SL. 2017. Mechanisms of fluorine accumulation in nitric thermal watersbulletin of the Tomsk polytechnic university. Geo Assets Engineering, 328(12), 105–115.

Sklyarov EV, Sklyarova OA, Lavrenchuk AV, Menshagin YuV. 2015. Natural pollutants of Northern Lake Baikal. Environmental Earth Sciences, 74(3), 2143–2155. doi: 10.1007/s12665-015-4201-5.

Sklyarova OA, Sklyarov EV, Och L, Pastukhov MV, Zagorulko NA. 2017. Rare earth elements in tributaries of Lake Baikal (Siberia, Russia).AppliedGeochemistry,82,164–176.doi:10.1016/j.apgeochem.2017.04.018.

Skuzovatov SYu, Belozerova OYu, Vasil'eva IE, Zarubina OV, Kaneva EV, Sokolnikova YuV, Chubarov VM, Shabanova EV. 2022. Centre of Isotopic and Geochemical Research (IGC SB RAS): Current State of Micro- and Macroanalysis. Geodynamics & Tectonophysics, 13(2), 0585. doi: 10.5800/GT-2022-13-2-0585.

Speizer GM. 2010. Resort and Recreational Potential of Irkutsk Region. The Bulletin of Irkutsk State University». Series «Earth Sciences», 2, 190–216 (in Russian).

Suturin AN, Chebykin EP, Malnik VV, Khanaev IV, Minaev AV, Minaev VV. 2016. Te role of anthropogenic factors in the development of ecological stress in the littoral zone ofLake Baikal (water area of the Listvyanka settlement). Geography and Natural Resources. 6, 43–54 (in Russian).

Ten Brink US, Taylor MH. 2002. Crustal structure of central Lake Baikal: Insights into intracontinental rifting. Journal of Geophysical Research: Solid Earth, 107(B7), 2132. doi: 10.1029/2001JB000300.

Turutanov EK. 2018. The anomalies of gravity, deep structure and geodynamics of the Mongol-Siberian region. Irkutsk, Izd-vo IRNITU (in Russian).

Zamana LV. 2000. Fluorine in nitric hydrotherms of Transbaikalia. Russian Geology and Geophysics, 41(11), 1575–1581.

Zhmakin IA, Al-Galban LN, Markina AD, Panasenko AS. 2020. Assessment of the effect of fluorine compounds in drinking water on selected human health indicators. Tver State Medical University, 5, 39–49 (in Russian).

Zorin YA, Turutanov EK, Mordvinova VV, Kozhevnikov VM, Yanovskaya TB, Treussov AV. 2003. The Baikal rift zone: the effect of mantle plumes on older structure. Tectonophysics, 371(1-4), 153–173. doi: 10.1016/S0040-1951(03)00214-2.