ISSN 0742-0463, Journal of Volcanology and Seismology, 2025, Vol. 19, No. 1, pp. 13–29. © Pleiades Publishing, Ltd., 2025.

The Verkhne-Yuriev Thermal Springs: The Evolution of Chemical and Isotope Compositions (1952–2022) in Relation to Active Periods of Ebeko Volcano, Paramushir Island

E. G. Kalacheva[a, *], **T. A. Kotenko**[a], **E. V. Voloshina**[a], **D. Yu. Erdnieva**[a], **and D. V. Melnikov**[a]

[a] *Institute of Volcanology and Seismology, Far East Branch, Russian Academy of Sciences,*
bulvar Piipa 9, Petropavlovsk-Kamchatsky, 683006 Russia
**e-mail: keg@kscnet.ru*

Received April 16, 2024; revised July 29, 2024; accepted October 28, 2024

Abstract—This paper describes the chemical composition of the thermal waters discharging on the northwestern slope of the active Ebeko Volcano in the Yuriev River valley. We are using continuous multiyear observations of the evolution of chemical and isotope compositions to estimate the response of volcanic events to the state of the hydrothermal system. It is shown that phreatomagmatic eruptions of the volcano were preceded by a change in the chemical and isotope compositions of thermal waters caused by increased inflow of magmatic volatiles into the system. The springs are observed to show increased concentrations of anion-generating components (chloride, sulfate, and fluorine ions) with concurrent increases in heavier isotopes of oxygen and hydrogen (deuterium) toward "andesitic" water. Recalling that the changes were detected a few months before the eruption, we infer that such geochemical effects can serve as predictive markers when monitoring the state of the volcano.

Keywords: Yuriev River, Paramushir Island, hydrogeochemistry, thermal water

DOI: 10.1134/S0742046324700908

INTRODUCTION

Ebeko Volcano in the northern Paramushir is one of the more active volcanoes on the Kuril Islands. A local hydrothermal system is confined to its edifice. The principal geothermal reservoir lies at a depth of ~300 m from the crater zone, and contains a boiling ultra acid chloride–sulfate solution at a temperature >200–210°C (Kalacheva et al., 2016). Lateral runoff largely occurs in the northwest direction. The waters are discharged 2.5 km of the active crater in the Yuriev River valley as a series of high-discharge Verkhne-Yuriev gravity springs.

The Verkhne-Yuriev springs are a remarkable instance of ultra acid thermal waters (ASC water (**A**cid **S**ulfate-**C**hloride) (Taran and Kalacheva, 2020)). The main mechanism which generates such water consists in condensation of volcanic vapor in the near-surface conditions and/or dissolution of "acid" magmatic volatiles (SO_4, Cl, HF) in aerated groundwater resulting in a mixture of acids (Giggenbach, 1997; among others). Most ASC waters were detected and described in Japan (Kimbara and Sakaguchi, 1989; Sasaki, 2018) and on the Kuril Islands (Markhinin and Stratula, 1977; Kalacheva and Kotenko, 2013; Kalacheva and Voloshina, 2022; Kalacheva et al., 2016, 2021, 2022, 2023; among others). Such water is encountered in Indonesia (Delmelle et al., 2000; Mazot et al., 2008; Caudron et al., 2018; among others), in Argentina (Varekamp et al., 2009), in Colombia (Sturchio et al., 1988; Torres-Ceron et al., 2019) and in other countries lying along the Pacific coast. The most complete review of ultra acid volcanic waters worldwide that are discharged as thermal springs can be found in (Taran and Kalacheva, 2020).

The chemical and isotope compositions, the temperature of ultra acid waters are extremely variable. Apart from seasonal and short-term variations due to varying precipitation and snow melting, i.e., differing degrees of dilution, these waters experience considerable changes in the relations between components due to active periods of volcanoes whose edifices enclose hydrothermal systems. It has been shown for several cases that indicators of activity can be the SO_4/Cl ratio and the isotopic composition of sulfur in dissolved sulfate (see the review of Taran and Kalacheva (2020) and the references therein). As an example, the SO_4/Cl ratio increased in springs of Copahue Volcano simultaneously with the eruption of 2000 (Varekamp et al., 2009), which was related to the emplacement of new magma into the system and accompanied by degassing of the deep fuid during the ascent. Increased concentrations of sulfate ions and chloride ions (apart from other factors) which were recorded in 2018 in the crater lake of Malyi Semyachik Volcano provided evidence of a new period of its activity after a long quiescent time. This activity was seen as increased input of magmatic volatiles (HCl and SO_2 in the first place) into the volcano's hydrothermal system (Taran et al., 2021). At the same time, it was shown by studying the Obuki boiling springs whose geochemical monitoring has been conducted for 70 years now that a hydrothermal system can yield a response, not only before or during a period of the volcano's increased activity, but also after the lapse of many years since the event (Ueda et al., 2021).

Continuous monitoring observations of the Verkhne-Yuriev springs are not conducted because they are hardly accessible. The present authors have been carrying out surveys in the Yuriev River valley since 2003 whenever possible, resulting in a considerable amount of data that were in part used in publications over the years (Kalacheva and Kotenko, 2013; Kalacheva et al., 2016; Kalacheva and Voloshina, 2022).

Ebeko Volcano began to erupt in 2016, and the eruption had continued well into 2024. There is as yet no published evidence concerning the response of the hydrothermal system to the events occurring on the volcano. It was only in (Kalacheva and Taran, 2019) that we find information on changes in isotope composition (δD, $\delta^{18}O$) in the Verkhe-Yuriev springs during the period 2016–2017 compared with 2014. In addition, a mudflow went down along the Yuriev R. valley in September 2017 which has affected the riverbed (Kotenko and Kotenko, 2018). The changes also affected the area where thermal waters were discharged (Kotenko et al., 2020).

In view of the above, our goal in the present study is the evolution of the chemical composition of the Verkhne-Yuriev spring water in relation to changes in the state of Ebeko Volcano using the multiyear monitoring observations. The main tasks include the following: a) a description of the location and conditions of discharge of thermal waters as of August 2022; b) a detailed study of changes in the chemical and isotope compositions of spring water over the area, as well as over time; c) identification of possible causes for fluctuations in the major element concentrations and their interrelationships over time; d) the search for geochemical indicators for the response of the hydrothermal system to Ebeko eruptions.

This study is based on the results of the authors' own multiyear observations (from 2003 through 2022), as well as on all available published data and archival materials for the entire period of observation of the volcano (since 1952).

A SHORT DESCRIPTION OF EBEKO VOLCANO

Ebeko Volcano stands in the northern Vernadsky Range (Fig. 1). It has a complex structure. The main morphologic elements include several cones dating back to different times and having varying degrees of preservation, which have coalesced to make a common volcanic mountain range with several large craters on top (Melekestsev et al., 1993). According to the paper referred to, the formation of the volcanic edifice began ~2400 years ago. The first phase involved effusions of lava flows and the coming of pyroclastic material to give way later on to explosive phreatic/phreatomagmatic eruptions. The present-day phase of volcanic activity began with a large phreatomagmatic eruption of 1934–1935. The explosions were occurring in a north–south fissure on the bottom of the Sredny Crater and were accompanied by discharges of ash and large andesite bombs (Gorshkov, 1954). The next major episodes of activity occurred in 1963–1967, 1987–1989, and 2005–2011 (Belousov et al., 2021). The ongoing eruption began in the fall of 2016 and continues now (Kotenko et al., 2018, 2019, 2022, 2023; Walter et al., 2020; Belousov et al., 2021). The eruption products include andesite ash and bombs (Kotenko et al., 2023).

GENERAL CHARACTERIZATION OF THE VERKHNE-YURIEV THERMAL SPRINGS

The springs are situated in the upper reaches of the Yuriev River, which drains a large (up to 2 km in diameter) erosion caldera which was formed during the glacial period where the Pleistocene Vlodavets volcano had been (Rodionova et al., 1966) (Fig. 2). At present, the caldera is a westward-open amphitheater dissected by deep barrancos. The caldera scarps are about 300 m high. The extant parts of the volcanic edifice exposed in the caldera walls are composed of a sequence of hydrothermally altered opalized agglomerates alternating with lava flows consisting of two-pyroxene basaltic andesites (*Opyt ...,* 1966). The altered rocks occur in a total area of over 15 km^2, the visible thickness is 200–250 m (Zelenov et al., 1965).

The Verkhne-Yuriev springs began to be surveyed in the mid-20th century. They were discovered during a geological exploration survey of 1952, the first mention of and first data on the chemical composition of the water is contained in the Geological Report.[1] The springs were visited by researchers annually from 1955 through 1961, the sampling results for that period can be found in (Ivanov, 1957; Sidorov, 1966; Rodionova et al., 1966; among others). V.V. Ivanov (1957) was the

---

[1] *Vlasov, G.M.,* The Main Features of Geological Structure and Sulfur Deposits on Paramushir Island (Greater Kuril arc), Report on exploration work of the Paramushir Team no. 17 in 1952, Petropavlovsk-Kamchatsky, 1953.

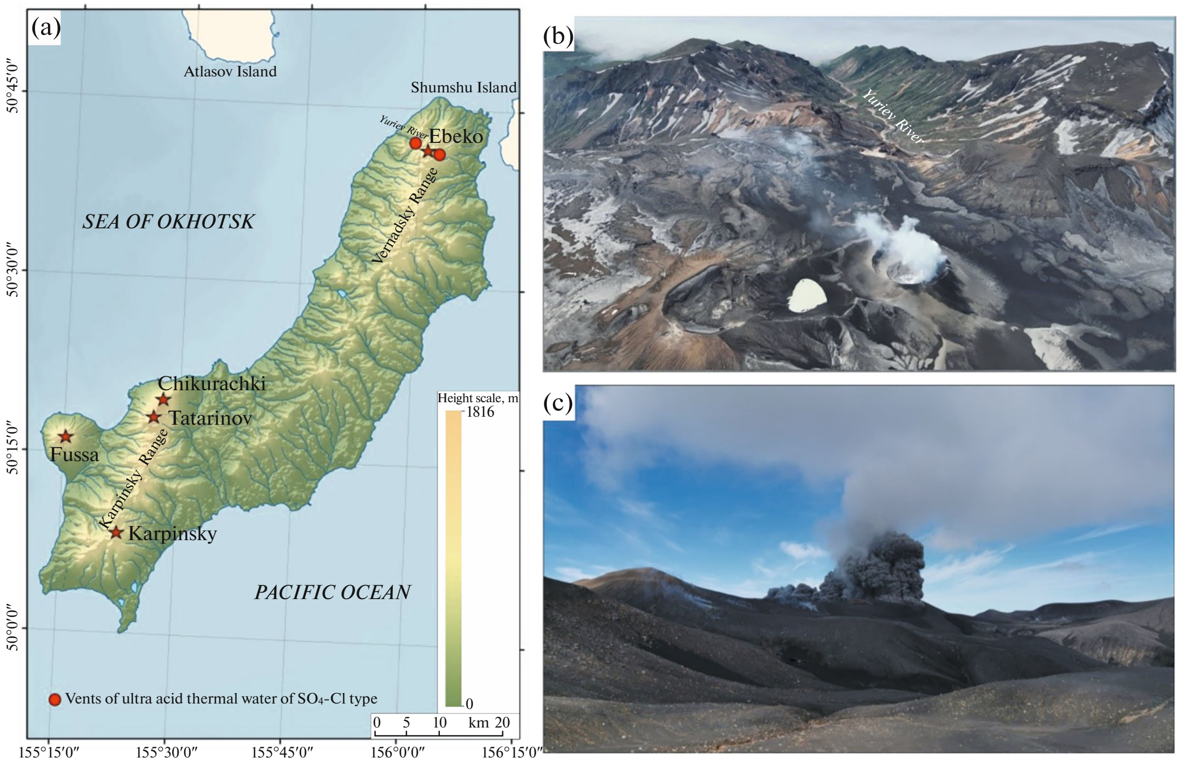

Fig. 1. Paramushir Island (a) and Ebeko Volcano: view of the volcano's craters and the Yuriev R. valley (b). Photographed by T. Kotenko. Near-summit part of volcano, starting ash emission from Korbut Crater and fumaroles of east slope (c). Photographed by E. Kalacheva.

first to determine the conditions of formation for the Verkhne-Yuriev springs as "fumarolic thermal fluids of deep formation" due to interaction between groundwater circulating in the volcanic edifice and volcanic gases. Their geochemical role in the output of rock-forming elements into the Sea of Okhotsk was considered in (Zelenov et al., 1965; Nikitina, 1978; Fazlullin, 1999; Kalacheva and Kotenko, 2013), the output volumes of magmatic volatiles can be found in (Kalacheva et al., 2016). The work of the recent decades (Bortnikova et al., 2006; Kalacheva and Kotenko, 2013; Kalacheva et al., 2016) provides data for a wide range of trace elements and discuss the conditions of formation for these thermal waters.

In spite of the considerable interest in the Verkhne-Yuriev springs, no detailed description of them has until now been made, with all the available publications providing just brief information. The most complete map showing the locations of the discharges as they existed in the 1980s is available in (Fazlullin, 1999). The present paper presents a detailed description of discharges of thermal water in the Yuriev River valley as of 2022 based on our own multiyear observations combined with aerial photographing and infrared surveys.

The discharges of thermal water occur in two separated groups in the area where the east–west fault along the river valley intersects northwest striking discontinuities, which are part of ring discontinuities.[2] The one group concentrates in a small area along Goryachy Creek, which is a left tributary of the Yuriev River. The other group begins somewhat down the Yuriev River near the front of a young lava flow which went down from Ebeko Volcano into the river valley (see Fig. 2).

The former group includes six main discharges plus a series of small discharges with low output values. The highest is "Spring no. 1" (see Fig. 2b, site V1) at a height of 560 m above sea level in a bench of the Goryachy Creek bed (which is "dry" during the summer–fall low water). Hot ($T > 80°C$) water issues from a fissure in hydrothermally altered rocks, resulting in deposition of colloidal sulfur leaving a yellow veneer on stones farther down the creek. Up until recently, the main outlet of thermal water was at water line on an inclined riverbed, which caused some difficulty for sampling during the summer. The spring–summer flood of 2022 collapsed part of the creek side and formed a scarp in the spring area. The result was to widen the discharging fissure, and the outlet moved to the right, beyond the influence of surface waters. The

---

[2] *Leonov, V.L.,* Assessment of the Thermal Water Potential in the Area of the Town of Severo-Kurilsk. Report, Petropavlovsk-Kamchatsky, 1990.

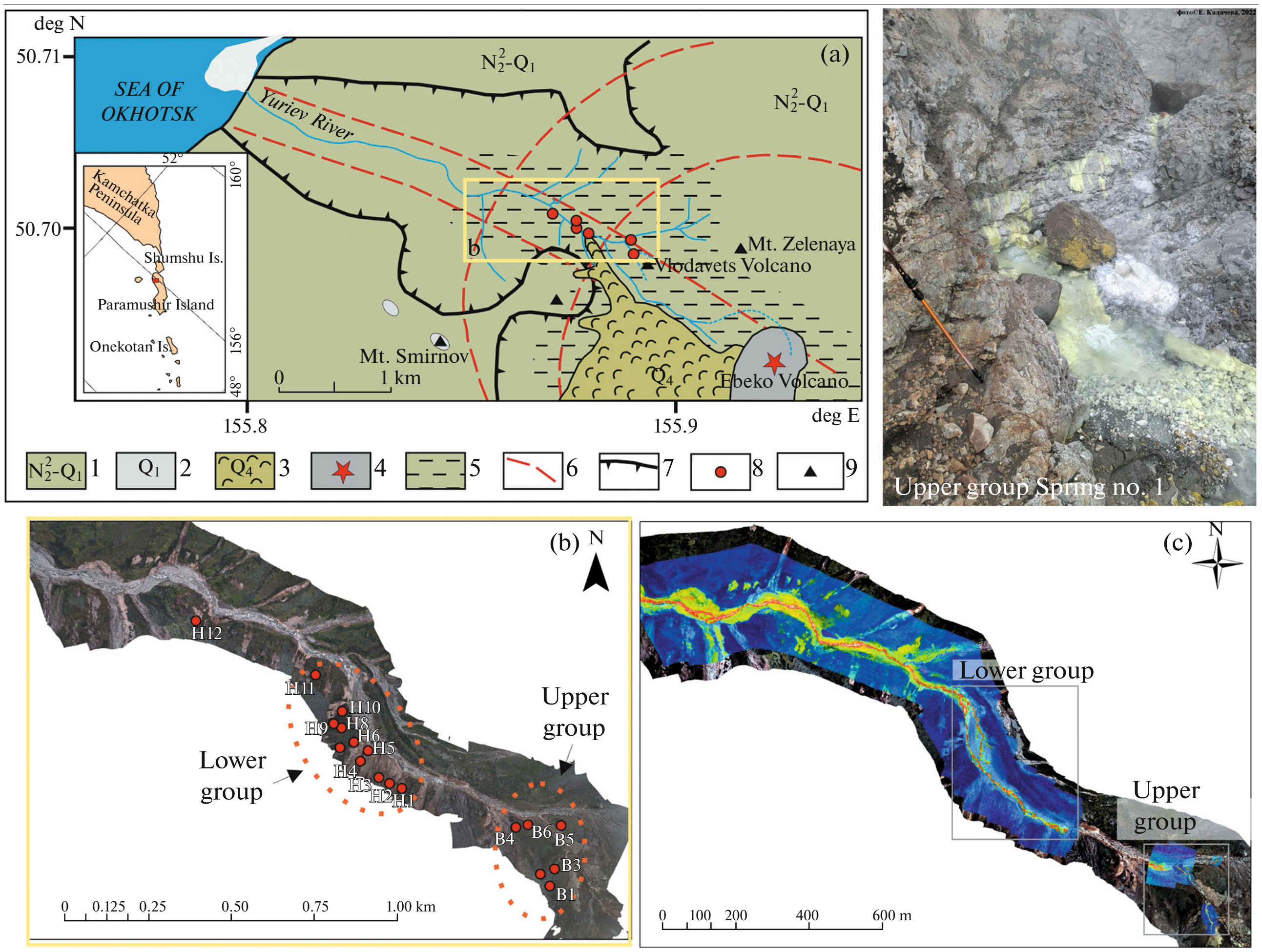

Fig. 2. A map showing the geological structure of the Yuriev R. valley (Kalacheva and Kotenko, 2013) (a). The inset shows the location of Paramushir. The orthophoto of upper reaches of Yuriev R. with sampling sites (b) and infrared image of Yuriev R. valley (c). (1) pyroclastic lava sheets consisting of andesites, basaltic andesites, and basalts (N_2^2–Q_1), (2) andesitic extrusions (Q_1), (3) andesitic and basaltic andesite lavas (Q_4), (4) present-day pyroclastic lava cone of Ebeko Volcano (Q_4), (5) area of hydrothermally altered rocks, (6) tectonic discontinuities (linear and ring discontinuities, (7) boundary of Vlodavets Volcano, (8) Verkhne-Yuriev springs, (9) extinct volcanoes.

rocks near the outlet are covered with a network of thin cracks exuding thermal water as well (see Fig. 2). “Spring no. 1” was chosen as a site of monitoring observation owing to several factors: 1) the location (the highest outlet); 2) the physical and chemical parameters (highest temperature and mineral content, the lowest pH) are the highest in the upper group of springs, and the same is true with respect to several elements. The zone of discharge can be identified based on a series of springs with low discharge rates issuing from fissures on both sides of the creek. The next large discharges are situated as far as in the mouth zone of the creek. There, at different distances from the creek bed, there are several springs with lower mineral content compared with “Spring no. 1” (4–6 g/L) and temperature (35–40°C), and higher pH (1.6–1.8). One of these springs is in a stone debris just near the mouth (spring “Ustievoi”, see Fig. 2b, site V4). Spring “Dalny” (see Fig. 2b, site V5) consists of two nearby outlets in the frontal part of the debris deposits that form a common creek emptying its waters in the Yuriev River itself. Another one (spring “Blizhny”, see Fig. 2b, site V6) issues from beneath the cemented deposits of an old mudflow fan. The beds of formed creeks due to springs “Dalny” and “Blizhny” harbors green thermophile algae. The outlets are at absolute heights of 500–517 m.

The other group of springs is of greater extent; it begins at the end of the Ebeko lava flow (see Figs. 2b, 2c) which descends toward the Yuriev R. bed. The distance between the mouth of Goryachy Creek and the first spring “U lavovogo potoka” (see Fig. 2b, site N1) is 350–360 m. The height of this outlet is 430 m. The discharge occurs from fissures in altered rocks that are partly overlain by fresh debris. Farther down the flow there are more than 20 local outlets of the same type whose discharge rates vary between 1–2 and 5 L/s at water line or in the Yuriev River bed itself. All of these have high temperatures ($T < 75°C$), high mineral content (M reaching 14 g/L) with low pH (<1.2). The discharge occurs on both sides of the river from hydrothermally altered lavas that compose its sides and bed. The discharge of thermal waters is accompanied by deposition of water-soluble, mostly sulfur-bearing minerals which are exposed on steam-affected patches at the edges of formed small creeks and on stones nearby. These deposits are washed away into the Yuriev R. bed during the periods of rain and floods. The extent of outlets in this group is 400 m, the height difference from the upper spring to the lower reaches 70 m. The Yuriev River, which receives all thermal runoff, is heated. Higher temperatures of the river can be followed through a great distance from the springs down the flow (see Fig. 2c).

The lower springs of the second group, including o.s. N11, had been at a distance of ~30 m from water line until the fall of 2017. They were characterized by a lower temperature (<50°C), a higher pH (reaching 1.6), and lower mineral content (7–9 g/L) compared with the springs near the water line. After a mudflow descended along the river valley in 2017 (Kotenko and Kotenko, 2018), which has “ploughed” the valley as far as the mouth, part of unconsolidated material was transported from the shore down the river. The riverbed deepened by more than 1 m in several river segments, while has been displaced for a few meters in other places. As a result, some springs were opened which had previously been under water, and could only be detected based on higher water temperature. The removal of the sedimentary cover along the left bank in the area of the lower springs has allowed us to determine the true outlets of some springs. It was found that they were discharged also from fissures in hydrothermally altered rocks up the river at distances that occasionally reached 100 m from the previous outlets. That is to say, some of the springs were buried under alluvial deposits, while their lower temperature and mineral content were controlled by cooling of water under the sediments during drainage beneath the sedimentary cover and possible mixing with groundwater runoff. The largest spring of this kind (spring “U uvala”, see Fig. 2b, o.s. N10) whose discharge rate is 8–10 L/s has the outlet on the right bank from beneath a ridge composed of deposits left by older mudflows. The spring has demonstrated the largest scatter in temperature and mineral content, which will be discussed below in more detail.

THE DATASET AND THE PROCEDURE

The waters of the Yuriev River and of the Verkhne-Yuriev springs (abbreviated in what follws as VYu springs) were sampled during the summer–fall low water during the last 20 years (in 2003, 2005, 2010, 2013, 2014, 2016, 2017, 2019, 2020, and 2022). The 2010 and 2014 results were in part used in (Kalacheva and Kotenko, 2013; Kalacheva et al., 2016). Physical and chemical parameters (pH, Eh, and temperature, °C) of water were measured using portable multiparameter analyzers. We separated the dissolved part and fine colloids from the suspended material by filtering water samples at sampling sites through a 0.45 μ membrane filter. To do subsequent bulk chemical analyses, we placed water samples in special plastic 0.5-L containers, while separate 15-mL containers were used for trace element analysis. No additional acidification was applied, since the natural pH of spring water is below 2.

The aerial photographing survey of the Yuriev R. valley was conducted on August 5, 2022 using a DJIMavic 2 Enterprise Advanced drone. This aircraft had a double camera (FC2403 model) which allows images to be taken in visible and thermal infrared ranges. The images were used to make two orthophotos (in visible and infrared ranges) of the river valley in the area of the springs.

The major components in water samples were analyzed by these authors at the Laboratory of Postmagmatic Processes, IVS FEB RAS. The concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+}, F^-, Cl^-, and SO_4^{2-} were determined using a Metrohm 883 ion chromatograph. The concentrations of SiO_2 and boron were determined by the photocolorimetry, and those of Al and Fe were found by atomic adsorption method. Geochemical data and the interpretation of results used the OriginPro 2024 program package.

THE RESULTS OF THE STUDIES AND A DISCUSSION

The Chemical Composition of Thermal Waters

Table 1 lists the major component compositions of VYu springs as of 2022. The anions of both groups are dominated by sulfur-bearing ions ($SO_4^{2-} + HSO_4^-$) and Cl^-. The main components of the cation part are Al^{3+}, Fe^{2+}, and Ca^{2+}. Both the Upper and the Lower groups have two kinds of outlets for thermal waters differing in their physical and chemical parameters and in mineral content. The springs confined to altered fissure lavas are characterized by high temperatures and mineral content, and by the lowest values of pH (1.2–1.4). The mean range of temperatures at these outlets is 80–90°C, the mineral content varies in the range 9–10 g/L. The concentrations of SO_4^{2-} and Cl^- reach 6.5 g/L and 2.2 g/L, respectively. The highest concentrations of Al^{3+} (425 mg/L), Ca^{2+} (312 mg/L), and Fe_{total} (234 mg/L), as well as that of SiO_2 (404 mg/L), were found in the springs of the Lower group. All springs typically have higher values of boron (2–5.3 mg/L) and manganese (3–7 mg/L). The springs that issue from rock debris or from beneath older

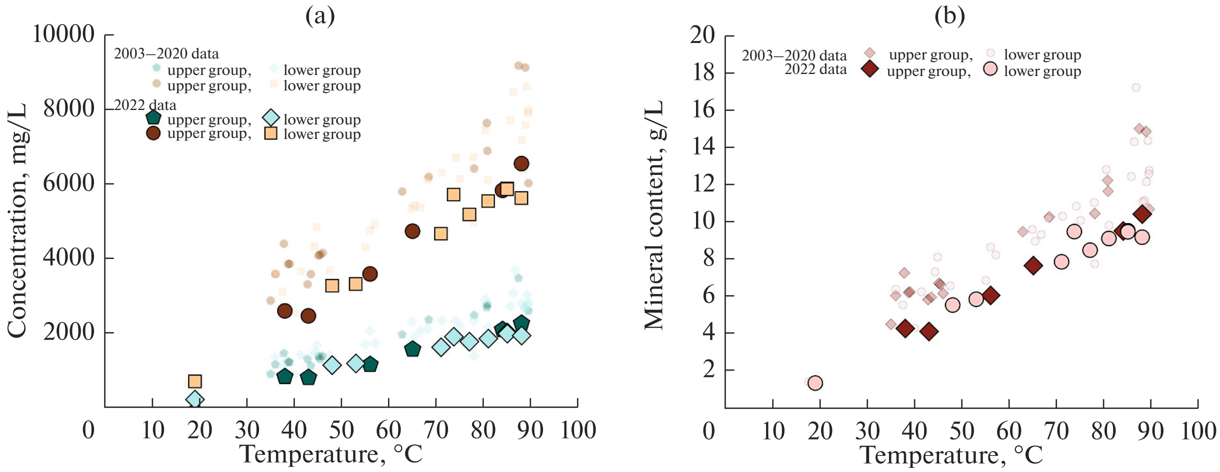

Fig. 3. Correlating the concentrations of Cl^- (blue) and SO_4^{2-} (brown) (a) and mineral content (b) with spring water temperature.

mudflow deposits have lower temperatures and mineral content and higher pH (see Table 1).

We previously noted (Kalacheva and Kotenko, 2013; Kalacheva et al., 2016) that the anion concentrations and the total mineral content of the VYu springs are directly related to their temperatures. The hottest springs generally have the highest concentrations of Cl^- and SO_4^{2-}, as well as the highest amount of dissolved salts (Fig. 3). There are no differences in the distribution of data points over groups, with all data points falling in one and the same field and making a common trend that reflects the positive correlation between components. This distribution indicates a substantial influence of dilution of thermal waters with cold groundwater in the discharge zone without the original hydrochemical water type being altered. It should be noted that the compositional data points for 2003–2020, while conforming to the general trend, mostly are above the 2022 data in the plots, which can be attributed to higher anion concentrations and to greater mineral content during the period.

The relationships between cations and anions in both groups of VYu springs also show high correlation (Fig. 4). In addition, the data point distribution indicates that the Lower springs are not derivates of the Upper group, but constitute an individual discharge of thermal water. In addition to the temperature dependence of the degree of groundwater dilution, each of the groups also shows a clear influence of groundwater on the lowering in the concentrations of elements. The relationships between major components remain constant for all springs, indicating common conditions of formation.

As shown in the review of Taran and Kalacheva (2020), many ASC waters have high fluorine concentrations and low Cl/F ratios, thus furnishing one of the significant indicators of a direct magmatic contribution into their formation (Fig. 5a, the zone of "magmatic water"). There is a compositional region of high temperature volcanic gases near that zone (relative concentrations of HCl, SO_2 + H_2S, and HF). The compositions of the Verkhne-Yuriev springs occupy a common compact region in the "magmatic water" zone with the mean molar SO_4/Cl ratio equal to 1 and concentrations of F^- equal to 50–60 mg/L. The arrangement of data points along a common line SO_4/Cl = 1 (see Fig. 5b) indicates simple mixing of meteoric water with a common original aqueous fluid which has high concentrations of sulfate and chloride ions.

The Verkhne-Yuriev springs typically have the total cation distribution (Al + Fe/Ca + Mg/Na + K) approaching that in rocks (see Fig. 5c). The original rock was assumed to be the recently published (Kotenko et al., 2023) compositions of Ebeko andesites of different ages. It is clearly seen that the data points that reflect the Verkhne-Yuriev compositions concentrate near to older rocks of Pleistocene age.

The Variations of the Chemical and Isotope Compositions of Thermal Waters Over Time

The Verkhne-Yuriev springs have been studied since the early 1950s. Comparative analysis of hydrochemical data for this long period of observation can help reveal individual features in the general variability of component composition for the springs and identify the response to the eruption activity of Ebeko Volcano. The main processes that control the varying chemical composition of ultra acid thermal waters over time may include: a) seasonal oscillations due to changes in meteoric recharge; b) transformation of the conditions that govern the formation of the waters in the recharging reservoir as a response to changing conditions of the host volcano.

Table 1. The chemical composition of the Verkhne-Yuriev springs as inferred from the 2022 sampling (mg/L)

Sample	Sampling site	Code	T, °C	pH_{lab}	F^-	Cl^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe_{total}	Al^{3+}	SiO_2	Mineral content, g/L
Upper group															
Os-75/22	"Spring no. 1" (l/b)	V1	88	1.25	54.3	2232	6517	168	75.5	307	127	180	329	315	10.32
Os-76/22	Spring below "Spr. no. 1" (l/b)	V2	84	1.28	50.2	2061	5798	162	74.6	302	125	180	334	316	9.42
Os-78/22	Spring (l/b)	V3	56	1.64	32.1	1123	3554	134	63.3	245	93.2	177	300	222	5.96
Os-80/22	Spr. "Ustievoi" (l/b)	V4	65	1.40	41.1	1535	4703	131	64.8	246	100	162	302	264	7.56
Os-74/22	Spr. "Dalny" (l/b)	V5	38	1.76	24.2	796	2560	84.1	53.6	147	51.7	76.6	219	162	4.18
Os-79/22	Spr. "Blizhny" (l/b)	V6	43	1.76	23.4	775	2429	81.1	49.5	141	55.8	77.6	214	172	4.03
Lower group															
Os-82/22	Spr. "U lavovogo potoka 1" (l/b)	N1	85	1.25	53.3	1988	5850	164	80.9	302	126	188	343	319	9.43
Os-81/22	Spr. "U lavovogo potoka 2" (l/b)	N2	85	1.26	51.9	1954	5832	161	82.4	296	123	194	356	312	9.38
Os-83/22	Spring (l/b)	N3	77	1.34	48.6	1737	5153	151	80.0	275	115	185	358	275	8.39
Os-84/22	Spring (l/b)	N4	74	1.38	51.4	1873	5688	166	82.6	313	122	234	431	404	9.38
Os-85/22	Spring (r/b)	N5	88	1.29	56.4	1903	5592	165	83.4	303	125	186	374	282	9.08
Os-86/22	Spring (r/b)	N6	81	1.38	54.5	1819	5512	168	83.7	303	126	183	425	320	9.01
Os-87/22	Spring (l/b)	N7	67	1.58	38.6	1375	3853	134	64.3	266	107	132	366	253	6.60
Os-88/22	Spring (r/b)	N8	71	1.47	44.3	1590	4634	154	77.7	286	117	157	388	294	7.76
Os-89/22	Spring (l/b)	N9	75	1.56	43.6	1636	4818	150	73.6	297	119	144	388	305	7.99
Os-90/22	Spr. "U uvala" (r/b)	N10	48	1.64	22.9	1104	3237	120	64.4	200	83.7	116	299	209	5.44
Os-91/22	Spr. "Krainy" (l/b)	N11	53	1.76	32.0	1153	3287	133	64.1	261	96.7	139	339	239	5.75
Os-92/22	Spr. "Limonitovaya stenka" (l/b)	N12	19	3.33	4.3	183	669	48.9	17.3	96.0	30.4	1.61	61.5	131	1.25

r/b right bank of Yuriev River, l/b left bank of Yuriev River.

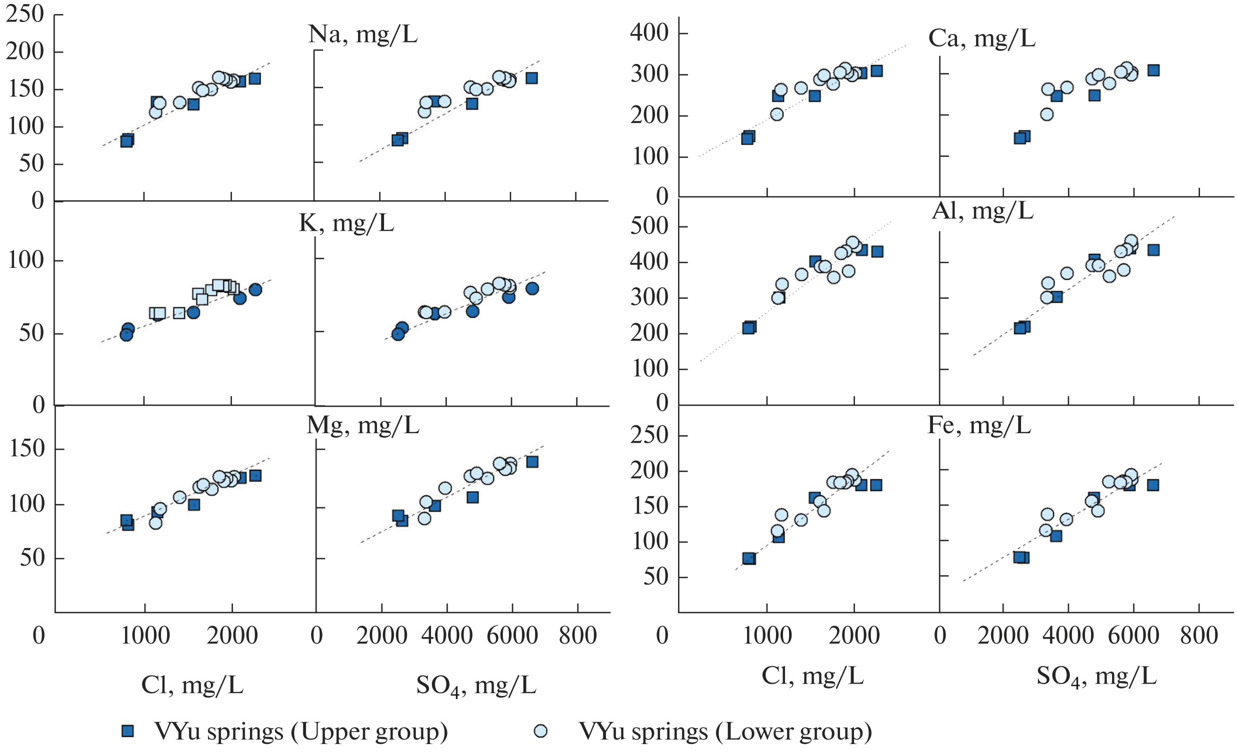

Fig. 4. Relationship between anions and cations at the Verkhne-Yuriev springs.

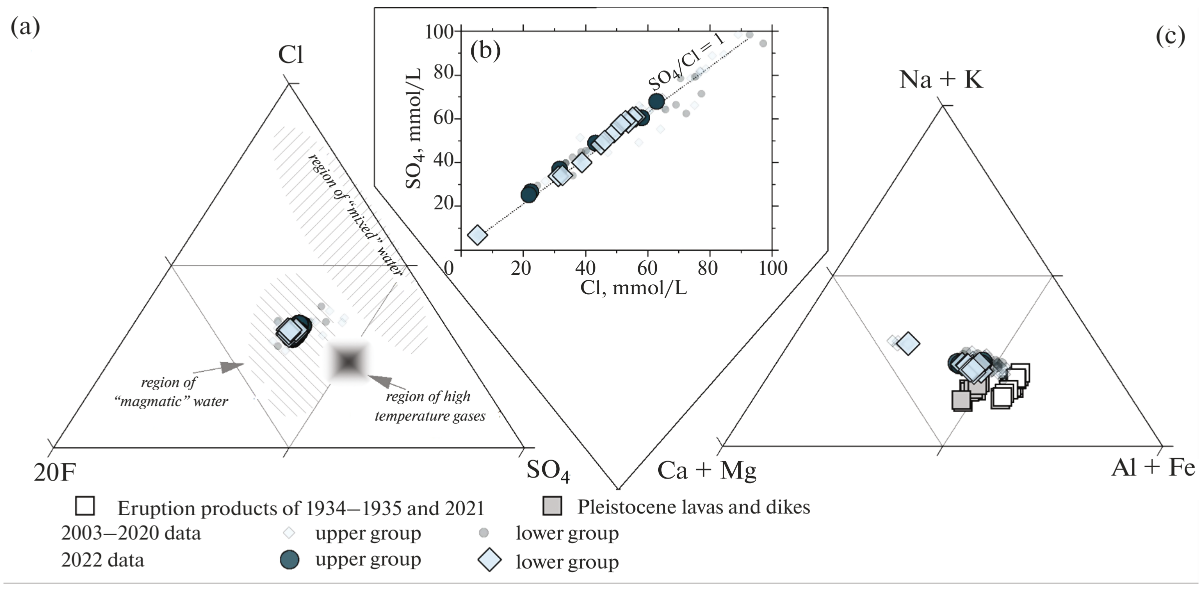

Fig. 5. Diagrams of relative major component concentrations in thermal waters (molar concentrations): anions (a), the SO_4/Cl ratio (b), cations (c). Rock compositions follow (Kotenko et al., 2023).

Our studies have shown that seasonal oscillations affect most strongly springs having lower temperatures and mineral content. All of these are confined to the unconsolidated sedimentary cover which favors their interaction with groundwater. The most remarkable example of changing physical and chemical parameters for a spring due to different degrees of impoverishment by near-surface waters is furnished by the "U uvala" spring (see Fig. 2b, o.s. N10). The concentration of chlorine ions in the water of that spring varied between 800 and 2250 mg/L, the temperature varied between 40 and 63°C, and the mineral content

Table 2. The chemical composition of the "U uvala" spring based on the 2005–2022 sampling results

Year	Sampling date	T, °C	$\mathrm{pH_{lab}}$	F^-	Cl^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe_{tot}	Al^{3+}	SiO_2
2005	17 Sep. 2005	40.0	1.57	30.2	851	2509	64	56.6	124	53	148	187	181
2010	18 Sep. 2010	64.8	1.53	n.d.	2269	5307	238	135	417	131	237	508	261
2014	13 Aug. 2014	41.4	1.44	n.d.	1383	3622	130	36.5	200	82.7	142	227	325
2016	31 Jul. 2016	44.8	1.63	34.1	1449	4363	148	105	234	90.2	268	438	234
2017	13 Jul. 2017	36.0	1.67	35.0	1352	4131	131	95.2	199	82.5	142	334	372
2019	13 Aug. 2019	66.7	1.61	57.1	2026	6340	209	134	325	138	249	540	197
2020	7 Aug. 2020	68.2	1.61	58.0	2056	6207	200	115	431	136	223	545	217
2022	5 Aug. 2022	48.0	1.64	22.9	1104	3237	120	64.4	200	83.7	116	299	209

n.d. means No data.

between 4 and 10 mg/L (Table 2). Unfortunately, no measurements of discharge rates were made during the sampling season, but a visual assessment of photographic and video materials taken in the past indicates increasing water volume when the lowest temperatures were recorded.

Figure 6 shows how the composition of spring water varied from year to year of sampling. The normalizing divisor relative to which all comparisons were carried out was chlorine ion as the most conservative element that does not make secondary mineral complexes when acid thermal and surface waters are mixed. A positive linear correlation is observed between temperature, mineral content, concentrations of macro cations and the concentration of Cl^-, with a similar dependence being observed between mineral content and temperature (see Fig. 3b). There is some scatter in the concentrations of Ca^{2+} (see Fig. 6b) which can be related to losses during the mixing of waters due to the formation of salts along the filtration path in unconsolidated deposits or to repeated dissolution as the fraction of thermal water increases during "drier" years.

In springs with high temperatures (>80°C) at a sufficiently stable temperature and pH, we observe variability in the concentrations of anions and some of the cations; the variability is unexplainable by simple mixing with groundwater or surface water (see Figs. 3, 4). Consider the changes in the concentrations of major components using two springs as examples that have the longest time series of geochemical data: "Spring no. 1" (Upper group) and the spring "U lavovogo potoka" (Lower group). These springs were first sampled in 1952.[1] During the entire period of observation (see Tables 3, 4), the concentrations of Cl^- and SO_4^{2-}, dissolved aluminum and iron were appreciably higher in the 1950s than during the later period of observa-

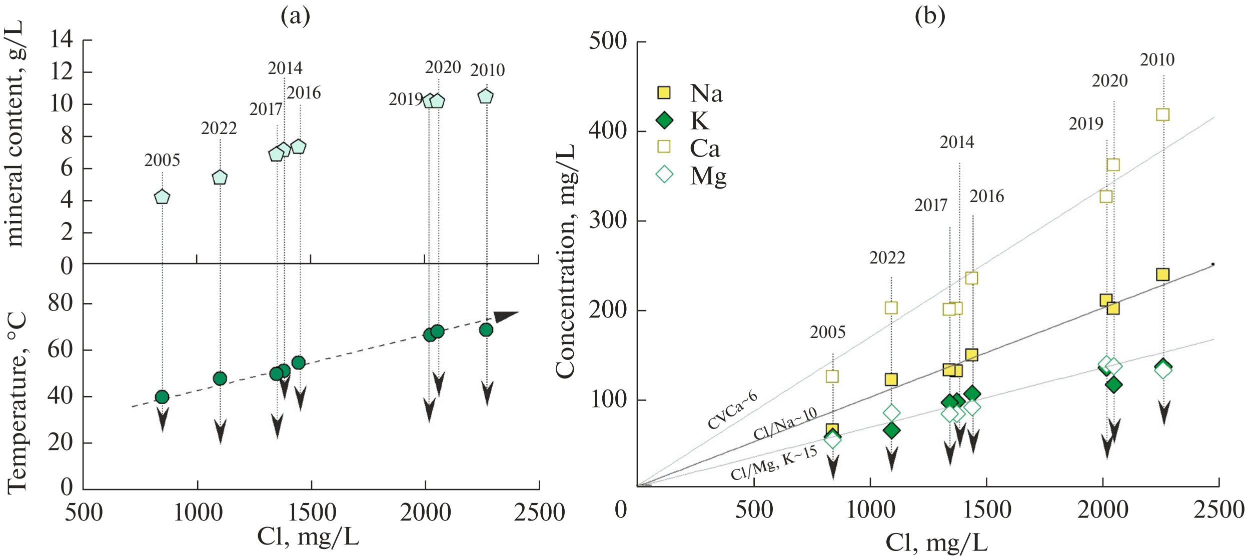

Fig. 6. The relationships Cl–(temperature, mineral content, cations) for the "U uvala" spring. Numerals at plots give year of sampling.

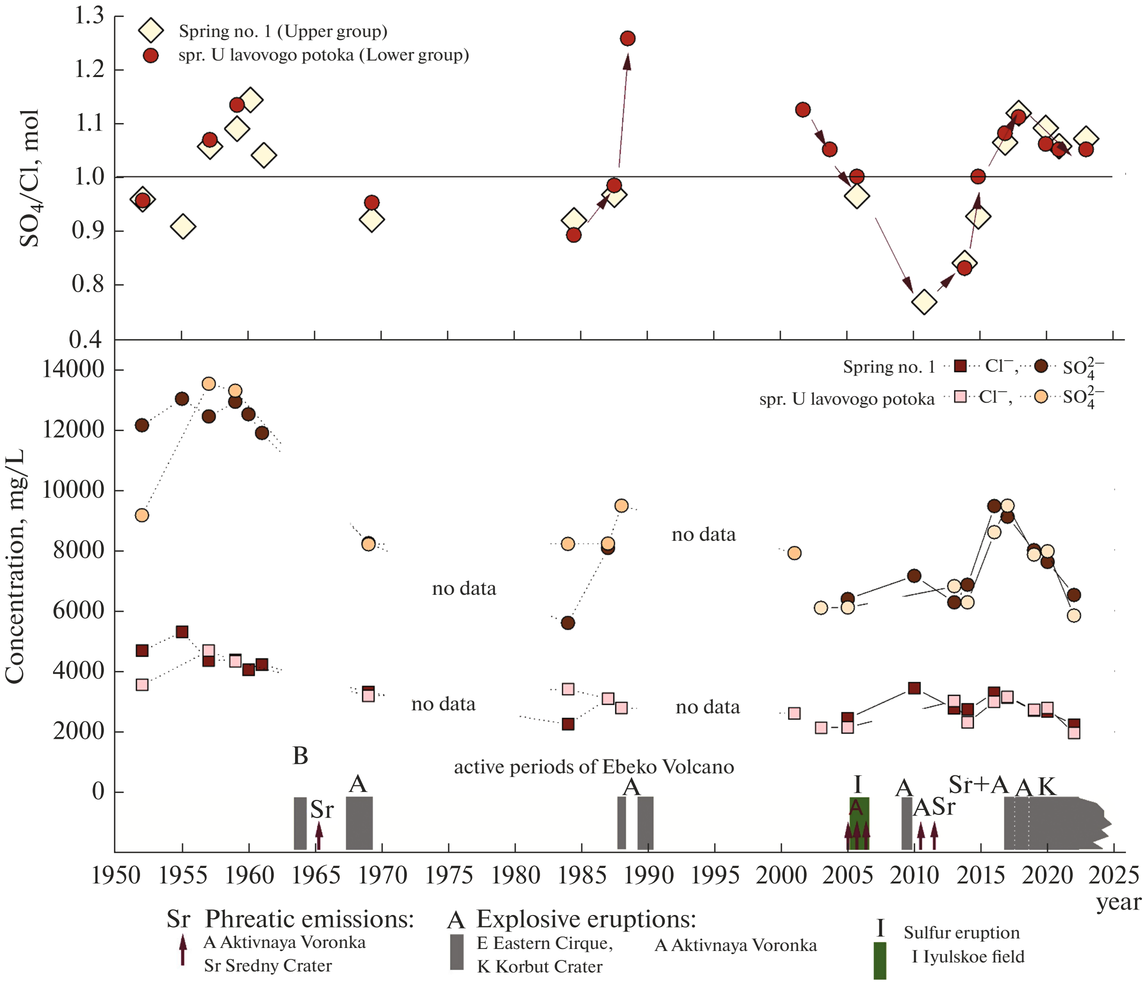

Fig. 7. Variation over time in the waters of Verkhne-Yuriev springs for concentrations of SO_4 and Cl and their ratio (SO_4/Cl) compared with periods of increased activity at Ebeko Volcano.

tion. The fluctuations in the concentrations of cations (Ca^{2+}, Mg^{2+}, Na) are not as large. For the initial period (1955–1961) the records tell us about the maximum water temperature (94–95°C) and the lowest pH (0.86). Mention of low temperature fumaroles in the upper reaches of the Yuriev River also dates back to that period (Zelenov et al., 1965).

Figure 7 shows the variation in the concentration of main anions and in their relationships to periods of higher Ebeko activity. This correlation was studied by ourselves previously (Kalacheva and Kotenko, 2013; Kalacheva et al., 2016), but we have not succeeded in drawing an unambiguous inference, because we relied on an incomplete data set, which should have included the precursory period before eruptions, the eruption time, and the aftereruption period. During the last eight years (from 2016 onward) we have acquired geochemical information which supported the response of the hydrothermal system to events occurring at Ebeko Volcano.

It should be noted that the highest concentrations of main anions were recorded during the initial period of observation of the VYu springs; this could have been due to a higher hydrothermal activity of Ebeko as a whole. During that period the Sredny crater of the volcano contained the thermal lake Goryachee reaching 200 m across and 20 m deep. The mean water temperature was 30–35°C, reaching 90°C where underwater steam-gas vents operated. The lake water was ultra acid with pH reaching 1.3, had a SO_4–Cl–Na composition and a mineral content reaching 4.7 g/L. Vigorous fumarolic and hydrothermal activity was observed around the lake (Gorshkov, 1954; Ivanov, 1957; Zelenov et al., 1965). A large intensively degassing spring was situated on the south shore, almost at brink of water, whose pH was below 1 and temperature was 77°C (Ivanov, 1957). The water (Q ~ 1–2 L/s) was issuing from a wide fissure (reaching 10 cm across) and came into the lake. Since the 1960s the hydrothermal activity at the Sredny crater began to decrease (*Opyt ...,* 1966), practically disappearing by the mid-

Table 3. The chemical composition of “Spring no. 1” water (1952–1922), mg/L

Year	Sampling date	T, °C	pH_{lab}	F^-	Cl^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe_{total}	Al^{3+}	SiO_2	Reference
1952		n.d.	n.d.	n.d.	4677	9116	n.d.	n.d.	540	225	500	n.d.	n.d.	Vlasov, 1953 (Report)
1955		95.0	0.86	52.0	4928	8854	287	268	344	267	417	608	n.d.	Ivanov, 1957
1957		90.0	1.32	n.d.	4346	12407	395	190	478	230	595	1023	256	Zelenov, 1972
1959		90.0	1.15	n.d.	4380	12895	385	260	251	204	599	996	326	Zelenov, 1972
1960		94.0	1.08	79.9	4042	12482	351	230	463	210	461	994	273	Rodionova et al., 1966
1961	August 1961	95.0	1.25	n.d.	3220	11861	278	248	404	196	526	989	260	Markhinin and Stratula, 1977
1969		85.5	1.26	11.3	3305	8224	327	156	421	179	392	612	270	Nikitina, 1978
1984	August 1984	85.0	1.48	52.8	2252	5595	166	95	341	134	376	475	284	Fazlullin, 1999
1987	September 1987	84.0	1.14	86.6	3008	8067	220	125	376	140	314	636	242	Fazlullin, 1999
2005	10 Sep. 2005	78.0	1.20	40.0	2446	6386	129	95	192	90	257	474	247	This paper
2010	17 Sep. 2010	87.4	1.27	n.d.	3440	7149	297	147	481	190	349	522	330	Kalacheva and Kotenko, 2013
2013	24 Aug. 2013	90.0	1.34	n.d.	2769	6278	276	98	411	173	227	480	286	This paper
2014	13 Aug. 2014	80.8	1.20	n.d.	2736	6861	187	128	230	150	228	526	502	Kalacheva et al., 2016
2016	31 Jul. 2016	80.4	1.12	61.0	3284	9454	255	159	305	159	224	572	263	This paper
2017	13 Jul. 2017	84.8	1.18	64.0	3461	9101	219	144	332	138	252	466	584	This paper
2019	13 Aug. 2019	89.5	1.19	68.5	2561	7995	250	136	379	172	312	520	197	This paper
2020	7 Aug. 2020	85.7	1.21	75.0	2661	7610	220	106	317	159	341	472	176	This paper
2022	5 Aug. 2022	89.1	1.25	54.3	2232	6517	166	75.5	307	127	180	329	315	This paper

n.d. means no data.

Table 4. The chemical composition of “U lavovogo potoka” spring (1957–2022), mg/L

Year	Sampling date	T, °C	pH_{lab}	F^-	Cl^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	$Fe_{tot.}$	Al^{3+}	SiO_2	Reference
1957		90.0	1.12	n.d.	4674	13492	328	220	543	241	673	1200	274	(Zelenov, 1972)
1959		90.0	1.19	n.d.	4330	13259	310	295	253	178	591	1079	314	(Zelenov, 1972)
1960	10 Sep. 1960	90.0	1.25	6.0	3284	8245	143	154	248	111	177	453	281	(Sidorov, 1966)
1969		84.0	1.3	12.5	3184	8193	317	162	409	176	383	627	271	(Nikitina, 1978)
1984	August 1984	90.0	1.26	98.0	3404	8206	273	166	421	195	447	769	348	(Fazlullin, 1999)
1987	September 1987	89.0	1.14	86.6	3089	8212	219	112	396	132	324	630	227	(Fazlullin, 1999)
1988	August 1988	81.8	1.1	80.3	2788	9469	191	128	356	160	360	629	214	(Fazlullin, 1999)
2001		87.0	0.98	n.d.	3140	9310	198	198	270	130	250	630	200	(Bessonova et al., 2006)
2003	26 Aug. 2003	81.0	1.41	51.0	2135	6094	119	116	208	114	225	432	219	This paper
2013	24 Aug. 2013	84.0	1.16	n.d.	3018	6811	294	104	470	183	246	634	288	This paper
2014	13 Aug. 2014	71.2	1.30	n.d.	2308	6277	168	134	226	132	80	468	418	(Kalacheva et al., 2016)
2016	31 Jul. 2016	86.7	1.03	79.1	3659	10670	312	180	436	172	553	580	480	This paper
2017	13 Jul. 2017	86.3	0.99	76.4	3153	9465	258	178	393	171	339	632	677	This paper
2019	13 Aug. 2019	88.1	1.39	70.1	2725	7849	256	143	394	176	292	520	192	This paper
2020	7 Aug. 2020	86.4	1.41	73.2	2787	7957	229	109	384	165	285	494	184	This paper
2022	5 Aug. 2022	85.0	1.26	51.9	1954	5832	161	82.4	296	123	194	356	312	This paper

n.d. means no data.

1960s (Skripko et al., 1966). The activity of the other fumarole fields did not stop during that time: the total fumarolic output of Ebeko as measured by instrumental means since 1959 (Nekhoroshev, 1960; Menyailov et al., 1988; Kotenko et al., 2022) was 0.9–2 thousand tons per day during intereruption periods. Compared with these data, the volcanic inflow that was required for an equilibrium state of Lake Goryachee, ~1.4 thousand tons per day as resulting from mass-balance and energy calculations for 1952 (Pasternack and Varekamp, 1997), seems considerable. The total gas emission of the volcano could exceed 2.3 thousand tons per day at the lowest estimate.

On the other hand, looking at the growing SO_4^{2-} to Cl^- ratio for the period 1957–1960, which gave way afterwards to a decrease, then working by analogy with our observations of a recent eruption (2016–2024), one could hypothesize after Belousov et al. (2021) that there were precursors to magma ascent, but the magma did not reach the surface, no eruption occurred, while an aureole with anomalous thermal and geochemical properties did reach the hydrothermal system. The consequences were seen as high concentrations of SO_4^{2-} and Cl^-, lower pH and, as a result, increased interaction between the brine and the host rocks, with the brine receiving great amounts of rock-forming elements, aluminum and iron in the first place (see Table 2).

Further decrease in hydrothermal activity in the volcanic craters might be due to changes in the plumbing system of the fumaroles (Nikitina, 1978) and to the displacement of the main fluid discharge to other areas. In particular, we mean the clogging of fluid-conducting channels and fissures as they are capped by minerals of hydrothermal origin. As shown by the 1950–1960 observations (Ivanov, 1957; Sidorov, 1966), thermal activity was decaying gradually, especially in the Sredny crater, over a long (more than 10–15 years) period, while fumarolic discharge in the Northeast field was observed to increase (Menyailov et al., 1988). The subsequent large-scale decrease in hydrothermal discharge on the volcano was most likely a response to decreased inflow of magmatic fluids into its hydrothermal system as a whole.

The rare sampling sessions from 1970 to 2003 do not either allow us to infer about the response of the hydrothermal system to increased activity of the volcano during that period (see Fig. 7 and Tables 3, 4), but a certain tendency of increasing SO_4/Cl ratio before the explosive events of 1987–1990 as described by Melekestsev et al. (1993) is discernible. Since 2003 a more or less regular monitoring of the chemical composition of the Verkhne-Yuriev springs has been conducted. The SO_4/Cl ratio has been steadily decreasing from 1.13 to 0.75 during the period of 2003 through 2010, gradually or in steps, which is difficult to say because no monitoring observations were made in 2006–2009. It is also impossible to come to an unambiguous conclusion whether the preceding decrease in that parameter was due to the “sulfur” eruption of 2005–2006 on the northeastern slope of the Severny crater (the Iyulskoe fumarolic field) (Kotenko et al., 2007) or was caused by the precursory occurrences before the 2009–2010 period of activity seen as a sequence of explosions from the Aktivnaya Voronka (Kotenko et al., 2010, 2012). No significant oscillations have been detected in the chemical composition of the water during the period. The practically continuous annual sampling of 2010–2022 helped identify the response of the system to volcanic events. The fall of 2016 saw a new phase of eruptive activity on the volcano that still continues. Practically 5 years before that event we observed the beginning of growth in the SO_4/Cl ratio which has continued until 2017. A sharp increase (compared with 2014) in the concentrations of Cl^- (by 20–59%) and of SO_4^{2-} (38–70%) in the water was recorded 2.5 months before the 2016 eruption began, which is a direct consequence of increasing amount of magmatic fluids coming into the hydrothermal system. The high anion values were also preserved in 2017. Starting in 2019 in spite of the fact that the eruption was still occurring, we observed a drop in the anion concentrations until the preeruption period of 2013–2014. However, the SO_4/Cl ratio which somewhat decreased by 2020 remains high (~1.1).

Going in parallel with the variation in the chemical composition of thermal water, heavier isotopes of $\delta^{18}O$ and δD were detected in the 2016–2017 samples compared with 2014 (Kalacheva and Taran, 2019). The plot (Fig. 8) is based on published data along with points for 2020 and 2022. The generalization of these results is as follows.

1) The isotope compositions of the Verkhne-Yuriev springs as inferred from the 2014 sampling localize near the meteoric water line, but with a noticeable positive shift in $\delta^{18}O$ and δD due to the mixing of magmatic vapor and meteoric waters (see Fig. 8a); these also show high correlation between the concentrations of Cl^- ions and the values of δD and $\delta^{18}O$ (see Fig. 8c).

2) The data points of 2016 and 2017 lie at the extension of the trend noticed for the 2014 samples (see Figs. 8a, 8b), while the concentration of chlorine ions increased in thermal waters simultaneously with the appearance of heavier isotope compositions (see Fig. 8c), which, according to (Taran and Zelenski, 2014), signals an increased fraction of magmatic water in the recharge of thermal waters and volcanic vapor.

3) We also identified increasing concentrations of SO_2, CO_2, and H_2 in all fumarole gases and HCl in the high temperature gases of Ebeko Volcano during the preeruption period from October 2015 to September 2016, as well as changes in the isotope composition of water in their condensates (Kotenko et al., 2022). That

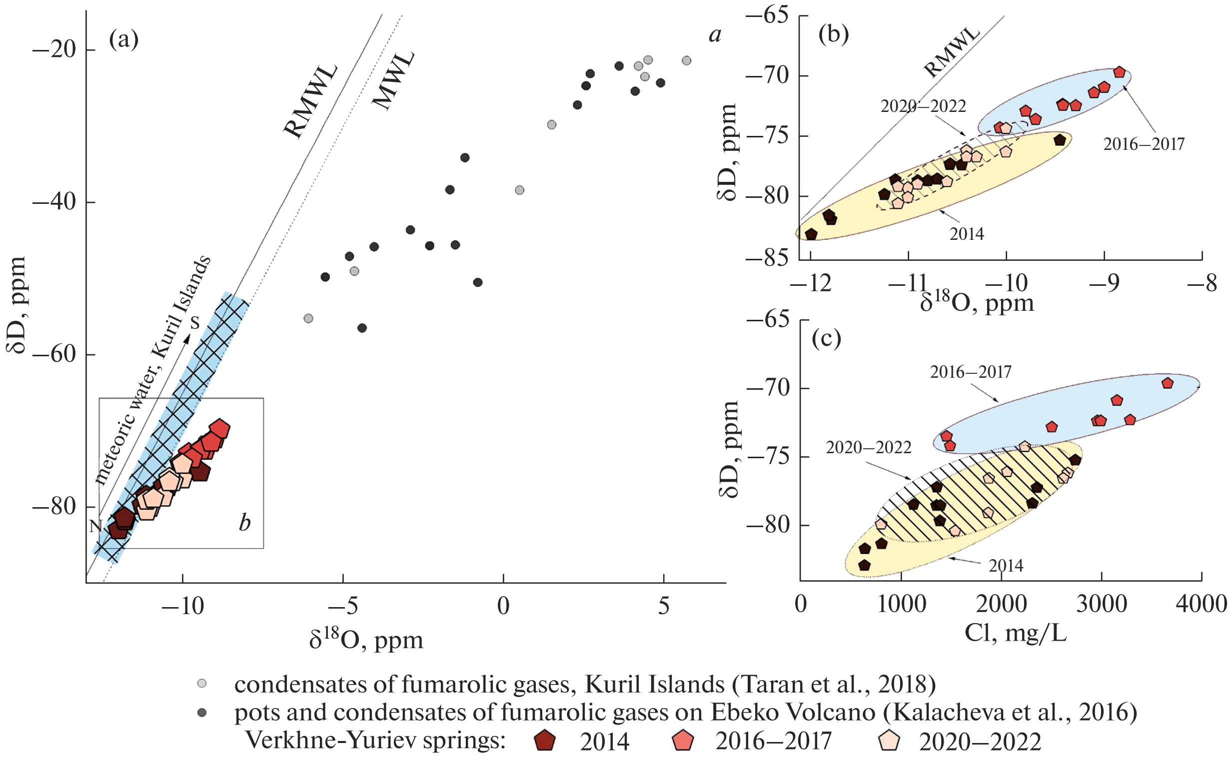

Fig. 8. The isotope composition of Verkhne-Yuriev springs (based on 2014–2022 data). (a) relationship between $\delta^{18}O$ snd δD (A marks the area of andesitic water, after (Taran et al., 1989]; RMWL regional meteoric water line, after (Cheshko, 1994), MWL global meteoric water line, after (Craig, 1961); the arrow N-S denotes the variation in the isotope composition of surface waters from northern to southern islands); (b) relationship between $\delta^{18}O$ and δD for Verkhne-Yuriev springs (enlarged fragment) highlighting characteristic data distributions over individual periods; (c) relationship between Cl and δD for Verkhne-Yuriev springs (2014–2022) highlighting characteristic data distributions over individual periods.

is to say, the concentrations of sulfate ions and chloride ions, as well as changes in the isotope composition of thermal water, were increasing simultaneously both in the near-summit part of the volcano and on its northwestern slope. In our opinion, this corroborates the presence of a common hydrothermal plumbing system.

4) As observed in 2020 and 2022, the Verkhne-Yuriev springs were recovering the preeruption 2014 values of isotope composition and concentration of chloride ions (see Fig. 8).

We have thus found the response of the hydrothermal system beneath Ebeko Volcano to its eruption starting in 2016. The response was occurring only during the precursory period which involved higher degassing of the volcano's plumbing system, and persisted during the initial phase of the eruption. After a period of time we again observed considerable lowering, primarily of sulfate ions and chloride ions. Indeed, the year 2022 saw the lowest values for the entire history of observation. We can well hypothesize that the hydrothermal system will be "diluted" with meteoric waters also later, while the eruption continues. Noticeable changes were also recorded in fumarolic gases around the summit, which provides evidence of a common hydrothermal plumbing system. Degassing of fresh rhyolite magma produces an aureole before its front having anomalous thermal and geochemical properties and which is the first to reach the hydrothermal system (Belousov et al., 2021), causing preeruption changes, including changes in the chemical and isotope compositions of thermal water and fumarolic gases due to increasing flow of acid gases (primarily SO_2 and HCl). These changes were first recorded 3–4 months before the eruption started, but more likely they began somewhat earlier, since thermal water was not sampled in 2015. The slow conditions of water exchange in the volcanic edifice resulted in the anomalous parameter values persisting into the initial eruption period. After a magma body breaks through the hydrothermal system, the cooling part of magma that has released part of the gases isolates itself from the system. All eruption activity occurs through the front of the flow, little gas coming into the hydrothermal system. It may well happen that the time of response for the Verkhne-Yuriev springs to a change in the volcano's state, from the precursory phase to its beginning, and the time of return to the "normal" state, lasts 1–2 years and depends on the rate of magma ascent and the water exchange rate. This hypothesis requires additional monitoring observations of the chemical and isotope compositions of the water.

CONCLUSIONS

A unique type of thermal volcanic waters is discharged in the Yuriev River valley on the northern Paramushir Island. The water has a sulfate–chloride composition with pH = 1.2, temperatures reaching 85–90°C, and a mineral content reaching 10–11 g/L. The discharge is carried out by two groups of the Verkhne-Yuriev springs. High correlations between anions and cations, between physical and chemical parameters, indicate a common source.

The variation in the chemical composition of thermal water is due to seasonal oscillations and as a response to changes in the state of the host volcano. Seasonal oscillations are greater in the waters of the springs confined to the unconsolidated sedimentary cover. The springs in the main zone of thermal output with high temperatures (>80°C) show variability in the anion concentrations due to periods of activity at the volcano. Preatomagmatic eruptions were preceded by a change in the chemical and isotope compositions of thermal waters owing to increased flow of magmatic volatiles coming into the system. The increase in the SO_4/Cl ratio in water began practically 5 years before the 2016 phase of eruption activity, and continued until 2017. A sharp increase (compared with 2014) in the concentrations of Cl^- (by 20–59%) and SO_4^{2-} (38–70%) in water was recorded 2.5 months before the 2016 eruption started, which was a direct consequence of increased supply of magmatic fluids into the hydrothermal system. High anion values were also observed in 2017. Beginning 2019, the anion concentrations were decreasing and reached the values recorded in the eruption period of 2013–2014. However, the SO_4/Cl ratio remained high (~1.1), while having somewhat decreased by 2020. In parallel with the changing chemical composition of thermal water, we detected heavier isotopes of $\delta^{18}O$ and δD in the 2016–2017 samples relative to 2014.

The results obtained here show that for the Verkhne-Yuriev springs the time of response to a change in the state of the volcano from the precursory phase before an eruption to the start of the eruption, and the time it takes to return to the “normal” state is 1–2 years, and is dependent on the rate of magma ascent and on the rate of water exchange.

Further study and more detail for the response of the volcano's hydrothermal system to the ongoing eruption require continued observation of the Verkhne-Yuriev springs. The most promising objects for monitoring observation are “Spring no. 1” in the Upper group and a spring near the lava flow front on Ebeko Volcano.

ABBREVIATIONS AND NOTATION

RAS	Russian Academy of Sciences
FEB	Far East Branch

ACKNOWLEDGMENTS

We are grateful to L.V. Kotenko and D.Yu. Kuzmin for invaluable help in multiyear field surveys.

FUNDING

This work was supported by ongoing institutional funding at the Institute of Volcanology and Seismology FEB RAS. No additional grants to carry out or direct this particular research were obtained.

CONFLICT OF INTEREST

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

REFERENCES

Belousov, A., Belousova, M., Auer, A., et al., Mechanism of the historical and the ongoing Vulcanian eruptions of Ebeko volcano, Northern Kuriles, *Bull. of Volcanology*, 2021, vol. 83, Art. 4.

Bortnikova, S.B., Bessonova, E.P., Trofimova, L.B., et al., Hydro geochemistry of gas–hydrothermal springs of Ebeko Volcano, Paramushir Island, *Vulkanol. Seismol.,* 2006, no. 1, pp. 39–51.

Caudron, C., Bernard, A., Murphy, S., et al., Volcano-hydrothermal system and activity of Sirung volcano (Pantar Island, Indonesia), *J. of Volcanology and Geothermal Research,* 2018, vol. 357, pp. 186–199.

Cheshko, A.L., The generation of main types of thermal water in the Kuril–Kamchatka region based on isotopic studies (D, ^{18}O, $^3He/^4He$), *Geokhimiya,* 1994, no. 7, pp. 988–1001.

Craig, H., Isotopic variations in meteoric waters, *Science,* 1961, no. 133, pp. 1702–1703.

Delmelle, P., Bernard, A., Kusakabe, M., et al., Geochemistry of the magmatic-hydrothermal system of Kawah Ijen volcano, East Java. Indonesia, *J. of Volcanology and Geothermal Research*, 2000, vol. 97, no. 1, pp. 31–53.

Fazlullin, S.M., The geochemical system of the Yuriev River (Kuril Islands): The conditions for supply and outflow of chemical elements in the river basin, *Vulkanol. Seismol.,* 1999, no. 1, pp. 54–67.

Giggenbach, W.F., The origin and evolution of fluids in magmatic-hydrothermal systems, in *Geochemistry of Hydrothermal Ore Deposits,* 3rd ed., N. Y.: John Wiley, 1997, pp. 737–796.

Gorshkov, G.S., Volcanoes on Paramushir Island and their state in the summer of 1953, *Byull. Vulkanol. St.,* 1954, no. 22, pp. 9–29.

Ivanov, V.V., Present-day hydrothermal activity of Ebeko Volcano on Paramushir Island, *Geokhimiya,* 1957, no. 1, pp. 63–77.

Kalacheva, E.G. and Kotenko, T.A., The chemical composition of waters and the conditions of origin for the Verkhne-Yuryev thermal springs (Paramushir Island, Kuril Islands), *Vestnik KRAUNTs, Nauki o Zemle,* 2013, no. 2, issue 22, pp. 55–68.

Kalacheva, E.G. and Taran, Yu.A., Processes controlling isotopic composition (δD and δ^{18}O) of thermal waters of the Kuril Island Arc, *J. Volcanol. Seismol.,* 2019, vol. 13, no. 4, pp. 201–215.

Kalacheva, E.G. and Voloshina, E.V., A geochemical characterization of thermal springs in the near-summit part of Ebeko Volcano (Paramushir Island, Kuril Islands), *Vestnik KRAUNTs, Nauki o Zemle*, 2022, no. 2, issue 54, pp. 6–19.

Kalacheva, E., Taran, Y., Kotenko, T., et al., Volcano-hydrothermal system of Ebeko volcano, Paramushir, Kuril Islands: geochemistry and solute fluxes of magmatic chlorine and sulfur, *J. of Volcanology and Geothermal Research*, 2016, vol. 310, pp. 118–131.

Kalacheva, E.G., Taran, Yu.A., Kotenko, T.A., and Voloshina, E.V., The geochemistry of acid thermal waters on Urup Island, Kuril Islands, *J. Volcanol. Seismol.,* 2021, vol. 15, no. 6, pp. 349–364.

Kalacheva, E.G., Taran, Yu.A., Kotenko, T.A., Voloshina, E.V., and Erdnieva, D.M., Ultra acid sulfate chloride waters of Baransky Volcano on Iturup Island, Kurils. The composition and output of magmatic and rock-forming components, *J. Volcanol. Seismol.,* 2022, vol. 16, no. 4, pp. 349–364.

Kalacheva, E.G., Taran, Yu.A., Voloshina, E.V., Tarasov, K.V., Melnikov, D.V., Kotenko, T.A., and Erdnieva, D.Yu., Crater lake Kipyashchee in the caldera of Golovnin Volcano: Water and gas geochemistry, output of magmatic volatiles (Kunashir Island), *J. Volcanol. Seismol.,* 2023, vol. 17, no. 1, pp. 1–16.

Kimbara, K. and Sakaguchi, K., Geology, Distribution of Hot Springs and Hydrothermal Alteration Zones of Major Geothermal Areas in Japan, *Report of Geological Survey of Japan,* 1989, vol. 270.

Kotenko, T.A. and Kotenko, L.V., Rain mudflows on September 4, 2017 in northern Paramushir Island, Kuril Islands, *Georisk,* 2018, no. 3, pp. 46–55.

Kotenko, T.A., Sandimirova, E.I., and Kotenko, L.V., Eruptions of Ebeko Volcano (Kuril Islands) in 2016–2017, *Vestnik KRAUNTs, Nauki o Zemle,* 2018, no. 1, issue 37, pp. 32–42.

Kotenko, T.A., Sandimirova, E.I., and Kotenko, L.V., The 2018 eruption of Ebeko Volcano, Paramushir Island, in *Materialy XXII regionalnoi nauchnoi konferentsii "Vulkanizm i svyazannye s nim protsessy", posvyashchennoi Dnyu vulkanologa* (Proc. XXII Regional Conference "Volcanism and Related Processes" Devoted to Volcanologist's Day), March 28–29, 2019, Petropavlovsk-Kamchatsky: IViS DVO RAN, 2019, pp. 82–85.

Kotenko, T.A., Kalacheva, E.G., and Voloshina, E.V., Present-day exogenous processes in the valleys of the Yuriev River (Paramushir Island) and Gorchichnyi Creek (Ketoi Island), and their effects on the discharge of thermal waters, in *Materialy XXIII Vserossiiskoi nauchnoi konferentsii, posvyashchennoi Dnyu vulkanologa* (Proc. XXIIi All-Russia Conference Devoted to Vocanologist's Day), Petropavlovsk-Kamchatsky: IviS DVO RAN, 2020, pp. 187–190.

Kotenko, T.A., Melnikov, D.V., and Tarasov, K.V., Gas emission on Ebeko Volcano, Kuril Islands in 2003–2021: Geochemistry, flows, and indicators of activity, *J. Volcanol. Seismol.,* 2022, vol. 16, no. 4, pp. 264–279. https://doi.org/10.1134/S0742046322040054

Kotenko, T.A., Smirnov, S.Z., and Timina, Y.Yu., The 2022 activity of Ebeko Volcano: The mechanism and ejecta, *J. Volcanol. Seismol.,* 2023, vol. 17, no. 4, pp. 259–277.

Markhinin, E.K. and Stratula, D.S., *Gidrotermy Kuril'skikh ostrovov (The Hydrothermal Occurrences on the Kuril Islands)*, Sugrobov, V.M., Editor-in-Chief, Moscow: Nauka, 1977.

Mazot, A., Bernard, A., Inguaggiato, S., et al., Chemical evolution of thermal waters and changes in the hydrothermal system of Papandayan volcano (West Java, Indonesia) after the November 2002 eruption, *J. of Volcanology and Geothermal Research*, 2008, vol. 178, pp. 276–286.

Melekestsev, I.V., Dvigalo, V.N., Kiryanov, V.Yu., et al., Ebeko Volcano, Kuril Islands: A history of eruption activity and the future volcanic hazard, Part I, *Vulkanol. Seismol.,* 1993, no. 3, pp. 69–81.

Menyailov, I.A., Nikitina, L.P., and Shapar, V.N., The chemical and isotopic compositions of fumarolic gases during the intereruptive period of Ebeko Volcano, *Vulkanol. Seismol.,* 1988, no. 4, pp. 21–36.

Nekhoroshev, A.S., Geothermal conditions and heat flow at Ebeko Volcano, Paramushir Island, *Byull. Vulkanol. St.,* 1960, no. 29, pp. 38–46.

Nikitina, L.P., *Migratsiya metallov s aktivnykh vulkanov v bassein sedimentatsii (Migration of Metals from Active Volcanoes to a Sedimentation Basin)*, Naboko, S.I., Editor-in-Chief, Moscow: Nauka, 1978.

Opyt kompleksnogo issledovaniya raiona sovremennogo i noveishego vulkanizma (na primere khr. Vernadskogo, o. Paramushir) (A Multidisciplinary Study of an Area of Recent and Neotectonic Volcanism: Vernadskii Range, Paramushir Island), *Tr. SakhKNII,* no. 16, Yuzhno-Sakhalinsk, 1966.

Pasternack, G. and Varekamp, J.C., Volcanic lake systematics, I. Physical constraints, *Bull. of Volcanology,* 1997, vol. 58, pp. 528–538.

Rodionova, R.I., Sidorov, S.S., Fedorchenko, V.I., and Shilov, V.N., *Geologicheskoe stroenie i sovremennaya gidrotermalnaya deyatelnost vulkana Vlodavtsa. Sovremennyi vulkanizm* (The Geological Structure and Present-Day Hydrothermal Activity of Vlodavets Volcano. The Present-Day Volcanism), in *Trudy Vtorogo Vsesoyuznogo vulkanologicheskogo soveshchaniya* (Proc. Second All-Union Volcanological Conference), September 3-17, 1964, vol. 1, Moscow: Nauka, 1966, pp. 98–103.

Sasaki, M., Classification of water types of acid hot-spring waters in Japan, *J. of Geothermal Research Society Japan*, 2018, vol. 40, pp. 235–243.

Sidorov, S.S., The 1963-1984 activity of Ebeko Volcano and the evolution of its hydrothermal activity during the previous period, *Byull. Vulkanol. St.,* 1966, no. 40, pp. 45–60.

Skripko, K.A., Filkova, E.M., and Khramova, G.G., The state of Ebeko Volcano in the summer of 1965, *Byull. Vulkanol. St.,* 1966, no. 42, pp. 42–55.

Sturchio, N.C., Williams, S.N., Gareia, P.N., and Lodofio, C.A., The hydrothermal system of Nevado del Ruiz volcano, Colombia, *Bull. of Volcanology,* 1988, vol. 50, pp. 399–412.

Taran, Y. and Kalacheva, E., Acid sulfate-chloride volcanic waters; Formation and potential for monitoring of volcanic activity, *J. of Volcanology and Geothermal Research*, 2020, vol. 405, Art. 107 036.

Taran, Y. and Zelenski, M., Systematics of water isotopic composition and chlorine content in arc-volcanic gases. The role of volatiles in the genesis, evolution and eruption of arc magmas, *Special Publications, Geological Society London*, 2014, pp. 410–432.

Taran, Yu.A., Pokrovsky, B.G., and Dubik, Yu.M., The isotope composition and origin of water in andesitic magma, *Dokl. Akad. Nauk SSSR,* 1989, vol. 304, no. 2, pp. 440–443.

Taran, Y., Zelenski, M., Chaplygin, I., et al., Gas emissions from volcanoes of the Kuril Island Arc (NW Pacific): Geochemistry and fluxes, *Geochemistry, Geophysics and Geosystems*, 2018, vol. 19, no. 6, pp. 1859–1880. doi.org/
https://doi.org/10.1029/2018GC007477

Taran, Y., Kalacheva, E., Dvigalo, B., et al., Evolution of the crater lake of Maly Semyachik volcano, Kamchatka (1965–2020), *J. of Volcanology and Geothermal Research,* 2021, vol. 418, *Art.* 107 351.

Torres-Ceron, D.A., Acosta-Medina, C.D., and Restrepo-Parra, E., Geothermal and mineralogic analysis of hot springs in the Puracé-La Mina sector in Cauca, Colombia, *Geofluids*, 2019, vol. 2019, Art. 3 191 454.

Ueda, A., Tanaka, T., Kusakabe, M., and Furukawa, T., Tamagawa hyper-acidic hot spring and phreatic eruptions at Mt. Akita-Yakeyama Volcano: Part 2. Secular variations of SO4/Cl ratios and their relationship to the phreatic eruptions, *J. of Volcanology and Geothermal Research*, 2021, vol. 414, Art. 107 242.

Varekamp, J.C., Herman, S., Ouimette, A., et al., Naturally acid waters from Copahue volcano, Argentina, *Applied Geochemistry,* 2009, vol. 24, pp. 208–220.

Walter, T.R., Belousov, A., Belousova, M., et al., The 2019 Eruption Dynamics and Morphology at Ebeko Volcano Monitored by Unoccupied Aircraft Systems (UAS) and Field Stations, *Remote Sensing,* 2020, vol. 12, no. 12, p. 1961.

Zelenov, K.K., *Vulkany kak istochniki rudoobrazuyushchikh komponentov osadochnykh tolshch* (Volcanoes as Sources of Ore-Forming Components of Sedimentary Sequences), Moscow: Nauka, 1972.

Zelenov, K.K., Tkachenko, R.P., and Kanakina, M.L., The rearrangement of ore-forming elements during the hydrothermal activity of Ebeko Volcano, Paramushir Island, *Trudy GIN AN SSSR*, 1965, no. 141, pp. 140–167.

Translated by A. Petrosyan