Active Volcanoes and Thermal Springs of Kunashir Island (Russia)

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Abstract. Since 2002, complex studies of all known thermal springs of Kunashir Island have been carried out. Of the four active volcanoes in the island, three volcanoes have stable hydrothermal systems. In addition to volcanoes, thermal springs in Kunashir are found on the coast and they are associated with tectonic faults. Despite the different morphogenetic types of volcanoes and their activity, the common patterns of zoning of hydrochemical types of thermal waters are typical for volcano-hydrothermal systems. On the periphery of the extrusive domes of the volcanoes, there are solfataric fields with outputs of gases and acid sulfate hydrotherms with temperatures up to 95 °C. Below the slope at a distance from the extrusive domes and solfataric fields an acid chloride-sulfate (sulfate-chloride) sodium hydrotherms with temperatures up to 91 °C are located. At the foot of volcanic edifices, at a considerable distance from the extrusions and outputs of solfataric gases, neutral chloride sodium thermal springs and steam are located. The isotopic composition of oxygen and hydrogen of different hydrochemical types of thermal waters is similar to the isotopic composition of local meteoric waters, which confirms the genesis of hydrotherms due to atmospheric waters with minimal participation of sea and "mantle" waters.

1. Introduction

Kunashir Island is located in the south of the Kuriles (figure 1a). Four active volcanoes are located in the Kunashir Island, three of which are at hydrothermal solfataric phase of activity: volcanoes Rurui, Mendeleev and Golovnin (figure 1b). Pleistocene-Holocene volcanic activity of the northern part of Kunashir Island associates with volcanoes Rurui, Tyatya, Smirnov and subvolcanic bodies of volcanoes Williams and Gedroits. In spite of the high density and variety of morphogenetic types of volcanic structures, hydrothermal activity in this area is insignificant. The largest active volcano in the island – Tyatya - erupted in 1973 for the last time. Currently, there are outputs of solfatar gases with a temperature of 80-90 °C in the craters of the central cone of Tyatya volcano, the outflows of thermal waters within the boundaries of the volcano edifice are not known. Modern hydrothermal and solfataric activity is manifested at the volcano Rurui, also in the northern part of the island there is a Prasolovsky thermal manifestation in the valley of Severyanka river and the thermal spring Dobry Klyuch on the Pacific coast. The central part of Kunashir island is represented by the active Mendeleev volcano, which is characterized by high hydrothermal and solfataric activity. The southern part of Kunashir includes the edifice of Golovnin volcano with intensive hydrothermal activity inside and outside the caldera.

The aim of the researches was to determine the current activity of Kunashir volcanoes, to clarify the geochemical characteristics and genesis of different types of thermal waters of the island.
2. Methodology
The author since 2002 has conducted the studies of thermal waters and solfataric outputs of Kunashir island. Each large spring was recorded on a photo and video camera, its exact coordinates were determined with using of the GPS device, the maximum water temperature and pH were measured. Thermal water samples were taken for analytical studies. Macroelements of 2003-2007 samples were determined by classical chemical analysis, which was carried out by standard methods in the testing laboratory of the FE branch of the FSU "Rosgeolfond" (Yuzhno-Sakhalinsk). The main cations, micro- and scattered elements of these samples were also analyzed by mass-spectral method at the Institute of Problems of technology of microelectronics and high-purity materials of RAS (Chernogolovka) with using of ISR-MS (Agilent 7500). Complete chemical analysis of thermal waters sampled in 2013-2014, was done by the accredited laboratory of JSC "Primorgeology" (Vladivostok). Isotopic definitions of oxygen and hydrogen in waters were performed in 2013 on the mass spectrometer Finigan MAT 252 at the Far Eastern Geological Institute of FEB RAS (Vladivostok).

![Figure 1](image-url)  
**Figure 1.** The geographical position of Kunashir Island (a), active volcanoes and thermal springs of Kunashir Island (b), Piper diagram for thermal waters of Kunashir Island (c), isotopic composition
(d) of local waters [7] and solfataric condensates [18, 21] (MWL – Meteoric Water Line, AMW – "Arc Magmatic Water" [18, 21, 24]). 1 – neutral thermal waters (pH 6–8); 2 – acid thermal waters (pH 1–4); 3 – freshwater of Serebryanoe lake [7] and rainwater of Kunashir Island [21]; 4 – solfataric condensates [18, 21].

3. Results

Dokuchaev ridge with an active Rurui volcano (1485 m) is located in the north of Kunashir Island. Neskuchnenskiye group of thermal springs and Dal’nyaya group of thermal springs were discovered in 2017 [1] on the north-western peripheral part of the Rurui volcano. First a brief description of Neskuchnenskiyei thermal springs was given by Markhinin E. K. [2, 3, 4], Gumeny Yu. K. and Neverov Yu. L. [5]. Further geochemical features of hydrotherms of this area were considered in the works of Cheshko A. L. [6], Zharkov R. V. [7]. A little-known Prasolovsky thermal spring is located in the valley of Severyanka river; it was examined in 2003 and 2013 [7]. A well-known spring Dobry Klyuch (Good Spring) is on the Pacific coast, it was studied by Russian scientists in details [6–9].

Area of Neskuchnenskiyei springs is formed with interstratified lavas, tuff breccias and tuffs of the Rurui volcano of the basalt composition of Pliocene age. Basaltic andesite are predominant among the effusive rocks. The outflows of the thermal waters are in solfataric areas, in the valleys of small streams and on the shore of the Sea of Okhotsk. On solfataric fields at an altitude of about 190 m a.s.l. acid (pH 2.2-2.6), sulfate calcium-sodium thermal water with a temperature from 40 °C to 92 °C discharges. The average temperature of the solfataric gases of 80-95 °C, the maximum temperature is 109 °C. Neutral (pH 7), sulfate-hydrogencarbonate calcium-sodium hydrotherms with temperatures up to 90 °C is located below the slope, in the valleys of the streams. Thermophilic algae often develop in these sources. In the southern part on the sea terrace there are neutral (pH 7), hydrogencarbonate-sulfate calcium-sodium waters with a temperature of 45-57 °C. The bottom of these sources is covered with thermophilic algae. On the shore among the boulders and pebbles the thermal water and steam with temperatures up to 100 °C is located. The chemical composition of coastal hydrotherms is mainly sulfate-hydrogencarbonate calcium-sodium, the temperature reaches 85-90 °C, pH is about 7.5. Analyzing the data on the chemical composition of Neskuchnenskiyei thermal springs, we noticed a change in the content of macro-and micro-components in the thermal waters of the springs with an increase in their hypsometric level. Also, the main characteristics of the waters of thermal springs changes: the temperature changes, the pH value decreases, gas composition varies from nitrogen to carbon dioxide, the chemical composition - from sulfate-hydrogencarbonate calcium-sodium to sulfate calcium therms.

Prasolovsky spring is located on the first river terrace in the low part of Severyanka river, which flows into the Sea of Okhotsk. Its nitrogen neutral (pH 6.9), sulfate calcium-sodium terms have a temperature of 37 °C. The Dobry Klyuch spring is located on the Pacific coast, its waters are slightly alkaline (pH 8), sulfate-chloride sodium with a temperature of up to 68 °C. Nitrogen prevails in the gas composition.

Mendeleev volcano (890 m) and its thermal springs are the most studied on the Kunashir Island. The beginning of exploring of thermal springs and solfataric fields was laid by Ivanov V. V. [8] and Markhinin E. K. [2–4] in the first half of the 1950s. A significant contribution to the study of the hydrothermal springs of the volcano was made by Sidorov S. S. [10], Dunichev V. M. [11], Barabanov L. N. [9], Cheshko A. L. [6] and many others. Since the late 1990s, the study of solfataric-hydrothermal activity of the volcano was continued by Rybin A. V. [12], Chudaev O. V., Chudaeva V. A., Chelnokov G. A., Bragin I. V. [13–16], Zharkov R. V. [17, 7], Kalacheva E. G., Taran Yu. A. [18].

Mendeleev volcano has passed a long and very complex history of development, as evidenced by three formed volcanic cones, subsequently destroyed as a result of explosive eruptions with the formation of caldera-crater depressions with a diameter of 6-9 km, 3-3.5 km and 1 km. After the formation of the last caldera-crater depression about 2500 years ago the growth of the dacite extrusion dome began. The relative height of the extrusion dome is about 400 meters, currently there
is no manifestations of activity on the dome. The next stage in the development of the volcano was the formation of craters of the explosion along the annular faults on the periphery of the extrusive dome, which at present time represent extinct and active solfataric fields [12]. The outflows of the thermal waters are concentrated on the solfataric fields and in the valleys of rivers and streams, as well as on the Pacific coast.

Modern hydrothermal and solfataric activity of the volcano is represented by the outputs of solfataric gases with temperatures up to 100 °C and the outflows of thermal waters of different chemical composition and mineralization, with different temperatures and pH values. The solfataras with temperatures up to 108 °C and numerous acidic (pH 1-3), carbonate, sulfate thermal (60-95 °C) springs with mineralization up to 1 g/l are met on solfataric fields at a height about 300-350 m a.s.l. and in the upper reaches of the streams. Below the slope of the volcano, in the valleys of streams and rivers, acidic hydrotherms of chloride-sulfate sodium composition with a mineralization of 2-4 g/l and a temperature of 60-91 °C discharge. At the foot of the volcano, there are outputs of neutral springs of mainly chloride sodium composition, with mineralization from 0.6 g/l in the river valleys to 15 g/l on the Pacific coast. The temperature of the springs on the periphery of the Mendeleev volcano varies from 30 °C to 80 °C. Mendeleev volcano with its various hydrochemical types of thermal waters discharged within the limits of solfataric fields, river valleys and streams or in the coastal part can be considered a classic example for revealing of the common regularities of formation and distribution of thermal waters of the areas of active volcanism.

The Golovnin caldera is located in the south of Kunashir Island. Inside the caldera solfataric outputs, thermal springs and acid thermal lakes relatively well studied, because the volcano is very accessible and interesting for researchers. The study of Russian researchers began in the 1950s, the first detailed description of the caldera of the volcano was conducted by Markhinin E. K. [3, 4], Sidorov S. S. [19], Baskov E. A. and Surikov S. N. [20], A. L. Cheshko [6] and many other researchers of the Kuriles made a great contribution to the study of hydrochemistry of thermal springs and lakes. Since the 2000s, the study of thermal springs was carried out by Chudaev O. V., Chudaeva V. A., Chelnokov G. A., Bragin I. V. [13–15], Zharkov R. V. [7], Kalacheva E. G., Taran Yu. A. [21]. Bathymetric survey inside the caldera lakes using sonar Kozlov D. N., Belousov A. B., Zharkov R. V. [22, 23] conducted in the years 2005-2015. The obtained data specified the depth of Kipiyashchee (Boiling) and Goryachee (Hot) lakes and determined the location of the main gas outputs on the bottom of the lakes.

Golovnin volcano (547 m) has a basement with diameter of about 10 km. The volcano is mainly formed with pyroclastics of andesite, andesite dacite and dacite composition. As a result of the powerful volcanic eruption of about 38000 years ago, a caldera with a diameter of 4.5 km along the ridge was formed. Later, the extrusion andesite dacite domes were formed in the caldera: Central Western and Central Eastern domes (in the center), the Krutoy and Podushechny domes (in the southern and northern parts, correspondingly). As the result of hydrothermal-phreatic eruptions the Kipiyashchee lake and Goryachee lake appeared on the periphery of the central domes. Several solfataric fields with the outputs of acid (pH 2-3.4), carbonate and sulfate hydrothermal springs with the total mineralization up to 3.5 g/l are located on the shores of the lakes.

It is very interesting that acid sulfate springs on the shore of Kipiyashchee lake coexist with neutral and alkaline (pH 6.0-8.5), carbon dioxide, sulfate-hydrogencarbonate calcium-sodium thermal springs. The temperature of the springs is 60-95 °C, the temperature of solfataric gases reaches 101° C. Acidic and neutral (pH 3.5-6.2), carbon dioxide, sulfate-chloride sodium-calcium Alyokhiskie springs with a temperature of 45-55 °C discharge the coast line of the Sea of Okhotsk of the volcano in the area of the Vneshnii (Outside) extrusive dome. In the middle part of Alekhniskie springs area, in the boundaries of tidal zone, steam outputs with a temperature up to 110 °C were found. Outside the Vneshnii dome there are neutral (pH 7.3), hydrocarbonate-sulfate calcium-sodium thermal springs with temperature up to 53 °C. Thus, the hydrochemical zonality of Golovnin volcano manifests itself in changing of the hydrotherms types from acidic sulfate in the areas of extrusion domes to neutral and alkaline ones outside the domes.
All volcano-hydrothermal systems of Kunashir Island are characterized by common regularities of changes in physical and chemical properties of thermal waters. In the diagram of the proportions of the macro-components of the thermal waters of active Rurui volcano, Mendeleev volcano and Golovnin volcano three main hydrochemical types (figure 1c) can be distinguished. Acidic sulfate hydrotherms with complex composition of cations are often found in the areas of extrusion domes of volcanoes on solfataric fields. Acidic chloride-sulfate (sulfate-chloride) sodium thermal springs are at the distance from extrusive domes and solfataric fields. A neutral chloride and hydrocarbonate-sulfate sodium thermal springs and outputs of steam are located on the periphery of volcanic edifices, at a considerable distance from extrusions, and outputs of solfataric gases. Such regularities are typical for many continental and island volcano - hydrothermal systems of the world.

The ratio of hydrogen and oxygen isotopes is often used to determine the genesis of thermal waters [24]. In Kunashir Island, the isotopic composition of hydrogen and oxygen of thermal waters is close to the line of meteoric waters (figure 1d), that indicates the predominance of meteoric waters in the feeding of hydrothermal systems. The isotopic composition of meteor waters of the studied region is known (δD = − 65‰, δ18O = − 9.1‰ [6]; freshwater of Serebryanoe lake δD = − 68.8‰, δ18O = − 9.7‰ [7]; rainwater in the area of Golovnin volcano δD = − 69‰, δ18O = − 9.8‰ [21]) and agrees well with local hydrotherms. The isotopic composition δ40Ar and ratio 40Ar/36Ar in some thermal springs of Kunashir is fully correlated with [20] the content and ratio of these elements in the air (δ40Ar content in the air is 0.0; the ratio 40Ar/36Ar in the air 295.6). The isotopic composition of helium and neon in thermal springs [14] also corresponds to local meteoric waters. Thus, the isotopic composition indicates the predominance of local meteoric waters in the feeding of different hydrochemical types of hydrotherms of Kunashir Island.

4. Conclusions
The modern studies have shown that of the Kunashir Island, of the four active volcanoes, three volcanoes have stable hydrothermal systems and several thermal springs are found on the coast and are associated with tectonic faults. Volcanic-hydrothermal systems are characterized by typical laws of the zoning of hydrochemical types of thermal waters. At the foot of volcanic edifices, at a considerable distance from the extrusions and outputs of solfataric gases, neutral (pH 6–8), chloride and hydrocarbonate-sulfate sodium thermal springs and steams are located. Below the slope at a distance from the extrusive domes and solfataric fields an acid (pH 1–4), chloride-sulfate (sulfate-chloride) sodium hydrotherms with temperatures up to 91 °C are located. On the periphery of the extrusive domes of the volcanoes, there are solfataric fields with outputs of gases and acid (pH 1–4), sulfate hydrotherms with temperatures up to 95 °C. The isotopic composition of different hydrochemical types of thermal waters is similar to the isotopic composition of local meteoric waters, which confirms the genesis of hydrotherms due to atmospheric waters.

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