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Hydrothermal Systems of the Shiashkotan Island (Kurile Islands, Russia)

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ABSTRACT

Two hydrothermal systems are distinguished in the Shiashkotan Island - North-Shiashkotan and Kuntomintar, whose thermal power makes 3800 and 4500 kcal/sec, correspondingly. These systems are located in the interior of Sinarka and Kuntomintar volcanoes. The volcanoes have composite edifices of Somma-Vesuvius type, heavily destroyed by seismic-tectonic processes. Specific development history of the volcanoes in the Holocene period conditioned the formation of two different hydrogeological environments in the northern and southern parts of the island, in which two different hydrothermal systems formed. The North-Shiashkotan hydrothermal system is a typical example of the island-arc type hydrothermal system associated with active andesite volcanism. Surface thermal manifestations of the system are distributed over 5-8 km of the outflow area and show typical vertical hydrochemical zoning. The Kuntomintar hydrothermal system belongs to the local type. Its surface manifestations are constrained by two thermal fields. The conducted geochemical studies have demonstrated that Kuntomintar volcano gasses are of magmatic origin. Their final composition has formed as a result of slow fluid ascent to the surface and due to significant dilution by meteoric waters under the near-surface conditions. High vent temperature of the gasses and a number of elevated prognostic ratios of S/Cl, S/C, CO_2/H_2 in their composition are indicative of possible intensification of the volcano fumarole activity.

1. INTRODUCTION

Shiashkotan is a 26 km long island belonging to the Kurile island-arc (**Figure 1**). Major morphological structures of the island are two Mid-Pleistocene-Holocene volcanic massifs – Sinarka and Kuntomintar (Stratula, 1969). Stratigraphic and geological settings of the volcanic massifs are characterized in Figure 1.

Each of the volcanoes developed in three stages (Stratula, 1969). At the initial stage, first somas of the volcanoes were formed. The second stage resulted in the formation of summit explosive calderas. Activity of the Kuntomintar volcano during Holocene led to the formation of several craters within the summit caldera, as well as to the development of a pyroclastic cone inside one of those craters. This period was also marked by the formation of a kettle-caldera in the western part of the volcano edifice. Caldera formation was significantly affected by oriented explosions, as well as glacial erosion and volcanic-tectonic subsidence. During the third stage of the Sinarka volcano development, an inner cone emerged within the North-Eastern part of the caldera. This period ended in squeezing out the central extrusive cone that took place in 1887 (Gorshkov, 1967), and ejections of incandescent lava. Quaternary volcanism of the Shiashkotan Island occurred at the background of intensive tectonic and volcanic-tectonic movements causing radial and sector faults (see Figure 1) along which modern hydrothermal activity is focused.

In 1960-1970th, hydrotherms of various chemical composition and physical-chemical properties discharging at the volcanoes' slopes and over the shoreline were studied in detail. At the same time, two hydrothermal systems – North Shiashkotan and Kuntomintar – were reported (Barabanov, 1976), and their thermal capacity was evaluated. In 2007-2008, thermal fields of the Sinarka volcano were partially examined (Zharkov et al., 2011). In June-July 2011, authors re-sampled thermal springs of the island and sampled gasses from the Kuntomintar volcano crater.

2. ORIGINAL DATA AND METHODS

Physical-chemical parameters of thermal spring and river waters (pH, Eh, dissolved salts abundances and temperature, ^{o}C) were immediately measured in situ using a portable Multi 340i/SET analyzer produced by the German WTW company. Water samples were filtered in situ using a membrane filter 0.45 µ. Samples were then placed into special plastic bottles 0.5 l in volume for further bulk chemical analysis.

Bubble liquid absorption method was applied for sampling fumarole gasses into vacuum bubblers 270-300 ml in volume made of quartz glass with alkaline absorbent (4M solution of KOH) (Nikitina et al., 1989). Titanium gas-sampling tube was also used. Fumarole gas condensate was sampled into a dry bubbler with forced gas pumping and cooling of walls with snow.

Analyses were conducted in the Analytical Center of IVS FEB RAS (analysts V.N. Shapar', I.F. Timofeeva, A.A. Kuzmina). Absorbed components in gas samples (H_2S, SO_2, HCl, CO_2) were determined by standard methods: potentiometric, iodometric, titrimetric analyses. Unabsorbed gasses (H_2, CO, CH_4, N_2, O_2, Ar, He) were analyzed by gas chromatography. Bulk chemical analysis of water samples including ions of Na^+, K^+, Ca^{2+}, Mg^{2+}, Al^{3+}, Fe^{3+}, Fe^{2+}, HCO_3^-, Cl^-, F^-, HSO_4^-, SO_4^{2-}, H_3BO_3, H_4SiO_4 was carried out using potentiometric, volumetric and colorimetric techniques.

Interpretation of hydrogeochemical data, calculations of deep temperatures by the cation geothermometer measurements, and graphic representation of thermal waters chemical composition were carried out using the AQUACHEM 5.1 software.

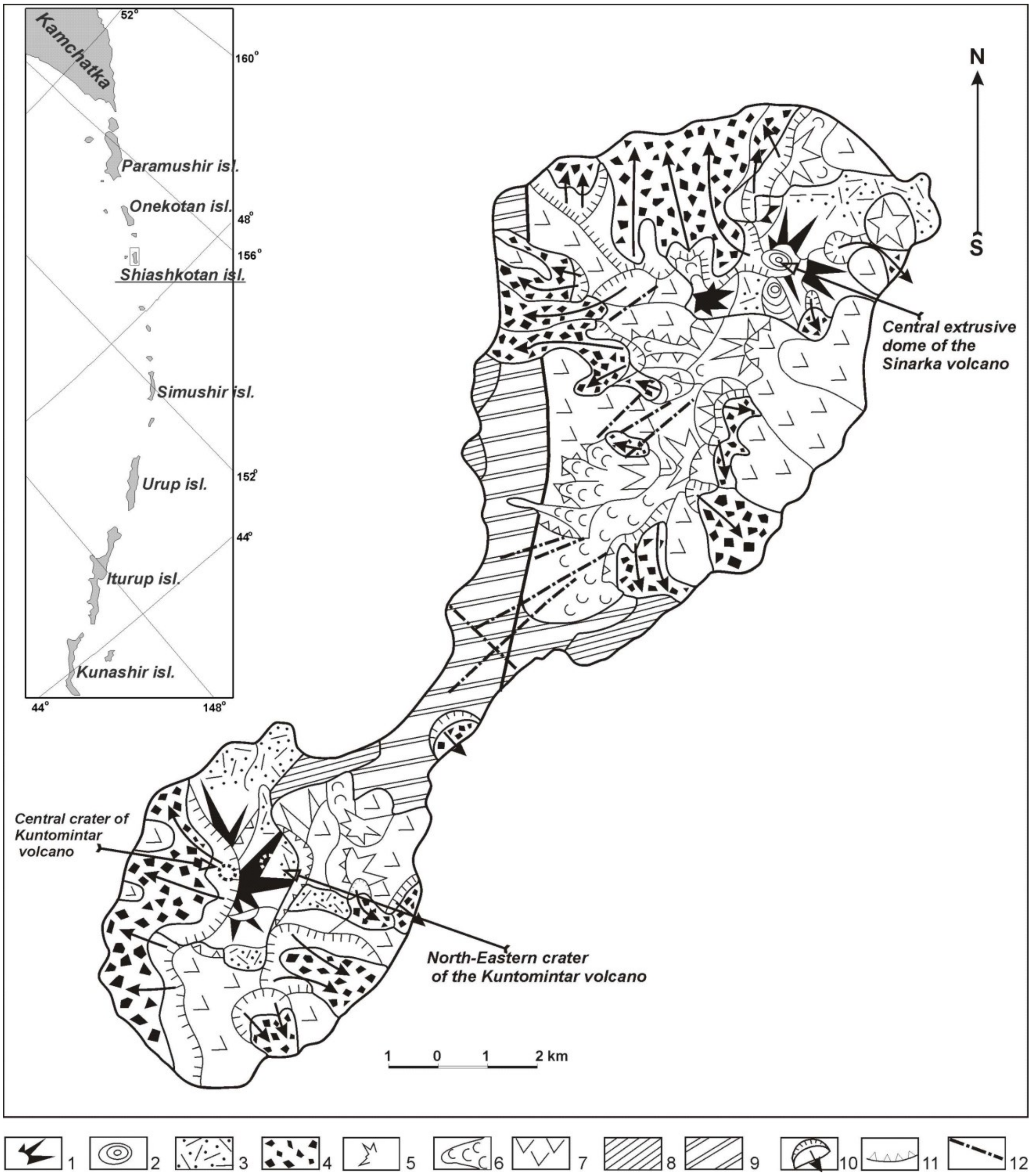

Figure 1: Geologic-geomorphological scheme of Shiashkotan Island (developed by (Novel…, 2005). Inset shows the location of Shiashkotan within the Kurile island ridge (Atlas… 2007). Holocene deposits (andesite): (1) large volcanic edifices, (2) extrusive domes, (3) pumice pyroclastic sheets, (4) landslide-debris deposits; Late Pleistocene-Holocene deposits (basalt-andesite rocks): (5) topographically pronounced pieces of volcanic edifices, (6) lava flows; Mid-Pleistocene deposits (andesites, basaltic andesites, basalts): (7) topographically indistinct pieces of volcanic edifices, (8) rock benches, (9) Neocene volcanogenic-sedimentary rocks (tuffites, tuffs and lavas of basaltic to andesitic composition), (10) volcanic-seismic-tectonic collapses, (11) erosion scarps, (12) visible dislocations with break in continuity.

2. THERMAL FIELDS AND SPRINGS OF SHIASHKOTAN

Nine groups of thermal springs have been distinguished on the island (Markhinin, Stratula, 1977). Three of them, including the Kuntomintar volcano crater, Central effusive dome and North-Eastern flank of the Sinarka volcano, are confined to the Quarternary volcanoes edifices, while the rest six groups are distributed over the coastal area of the island.

2.1 Thermal fields of the Kuntomintar Volcano

Thermal manifestations are focused within the Central and North-Eastern craters of the volcano (**Figure 2**). In the central crater, they are represented by steam-gas discharges and thermal springs distributed along the Craterny stream bed. Fig. 2 shows the location of major thermal fields and individual fumaroles. Gas temperature of F1-F4 fumaroles does not exceed 156 ºC. Fumarole F5, being a carbonized fissure 1.5 m long, shows gas discharge temperature of 480 °C.

Thermal waters discharge along the Craterny Stream (Figure 2). Markhinin and Stratula (1977) reported about 20 similar vents discharging ultra-acidic (pH 1.5-1.9) high-temperature (up to 80 °C) thermal waters with salinity up to 7.7 g/l at small rates (<0.3 l/s). One of the springs yielding 0.5 l/s (see Figure 2), was sampled by the authors (Table 1). Its measured temperature is 64 °C, pH=2.16, Eh +311 mV, salinity 5.4 g/l. Thermal water flows into the Craterny Stream bed. At the crater vent, the stream yields 4 l/s, with water temperature of 18.4 °C, pH=2.42, Eh=+265 mV.

By their chemical composition thermal waters from the Kuntomintar volcano crater and waters of the Craterny Stream sampled at the locations lower that the thermal fields, belong to the Al-Ca-SO_4 type (**Appendix 1**), with abundant Fe^{3+} (up to 195 mg/l). Composition of fumarole gas condensate from the Kuntomintar volcano crater is quite different from that of therms and corresponds to the Ca-Cl hydrochemical type with salinity of 1.3 g/l. The condensate shows the highest content of H_3BO_3 (81 mg/l among the other sampled water occurrences of the island.

North-Eastern flank of the Kuntomintar volcano (see Figure 1) has the shape of an amphitheatre 300 m in diameter, opened at the north with a large ravine whose walls are up to 100 m high. Its bottom is cut by a narrow streambed. Thermal activity was never reported in this crater by earlier researches. During the fieldworks conducted at the North-Eastern flank in 2011, 50 m above the ravine bottom (i.e. about 400 m above the sea level), the authors found two fumaroles. The rate of the upper, more powerful one, was about 10 m/s. Fumarole discharges are traced by a fissure. Steep slope and depth of the gorge made it impossible to get close to the fumaroles. According to the geologic-geomorphological scheme (see Figure 1), both sites with thermal occurrences are located at the summit caldera margin. Central crater marks the intersection point where the summit caldera borders the Zapadnaya kettle-caldera of the Kuntomintar volcano.

2.2 Thermal fields of the Sinarka volcano flanks

Hot springs of the Central extrusive dome (hereinafter CED) are located at the western flank of the volcano, below the dome foot (Figure 2). The thermal fields are all covered by iron hydroxide deposits 1-10 cm thick. Pressurized water flows out of small punctures through the deposits. Bright-green thermophilic algae are spread over the channels of thermal streamlets. Water temperature ranges 37-52 ºC, pH 2.6-3.2, Eh +230 - +270 mV, electro conductivity varies from 4100 µS/cm to 8040 µS/cm. Thermal waters flow from the sites into the Aglomeratovy Stream whose rate at the altitudes lower than the thermal fields makes 15 l/s, the temperature being 21.3 °C, pH=3.38, Eh=+211 mV.

Thermal springs of the Sinarka volcano CED are of heterogeneous composition, Ca^{2+}, Mg^{2+} and Al^{3+} cations, and Cl^- and SO_4^{2-} anions dominating (Appendix 1). Salinity ranges from 4.2 to 6.2 g/l. Maximum content of dissolved silica acid (459 mg/l) has been reported in the sample from Site 1. Besides, this sample shows high abundances of Cl^- (2.5 g/l), Na^+ (385 mg/l), Mg^{2+} (501 mg/l), Fe^{3+} (106 mg/l) and H_3BO_3 (49 mg/l). Chemical composition of the Aglomeratovy Stream water measured at the altitudes lower than the thermal sites is similar to that of thermal waters with lower salinity - 2.3 g/l.

Authors could not visit the North-Eastern hydrosolfatara field of the Sinarka volcano (NEHF) (see Figure 2a). So, in the present paper we use the data on the location of thermal manifestations and chemical parameters of thermal waters reported by (Markhinin, Stratula, 1977; Zharkov et al., 2011).

2.3 Coastal thermal springs

The western coastal area of the Shiashkotan Island hosts four major groups of thermal manifestations: Bashmachnaya, Vodopadnaya, Drobnaya, and Zakatnaya groups (see Figure 2), the total discharge rate of all the springs making about 50 l/sec. Spring discharge conditions are quite similar. Vents of thermal waters are confined to the dyke complexes. Depending upon the structure of the coastline, thermal waters discharge along the fissures in the lavas (Drobnye springs), from the bottom of the cavities between the boulders distributed over the coastline (Vodopadnye and Bashmachnye springs), or out of the coastline sand deposits (Zakatnye springs). Most of the springs are located along the tidal zone and are therefore exposed only during the ebb tide. Average extent of thermal vents along the coast ranges from 100 to 225 m. Individual vents yield about 0.2-0.3 l/s. Maximum measured water temperature of 63.8 °C was reported for the springs of the Vodopadnaya group. All of the coastal springs are characterized by the near-neutral reaction (pH=5.9-6.9). Occasionally, spring discharge pools are gurgled through by gas bubbles, some gas jets yielding up to 1.5 l/h. Water-permeable fissures are filled with cemented silt, rarer with chalcedony, calcite and pyrite.

Chemical composition of coastal thermal waters is presented in the Table (Appendix 1). Thermal waters belong to the Na-Cl type, with salinity ranging from 3.1 to 12.9 g/l. These waters are also characterized by high electric conductivity values ranging from 8310 µS/cm to 18260 µS/cm. Concentration of dissolved H_4SiO_4 varies from 110 mg/l to 280 mg/l, average content of H_3BO_3 being 40 mg/l. Amount of dissolved iron in the coastal spring waters is below the detection limit; however, all of the vents are coated with ochreous deposits and sinters formed by iron hydroxides.

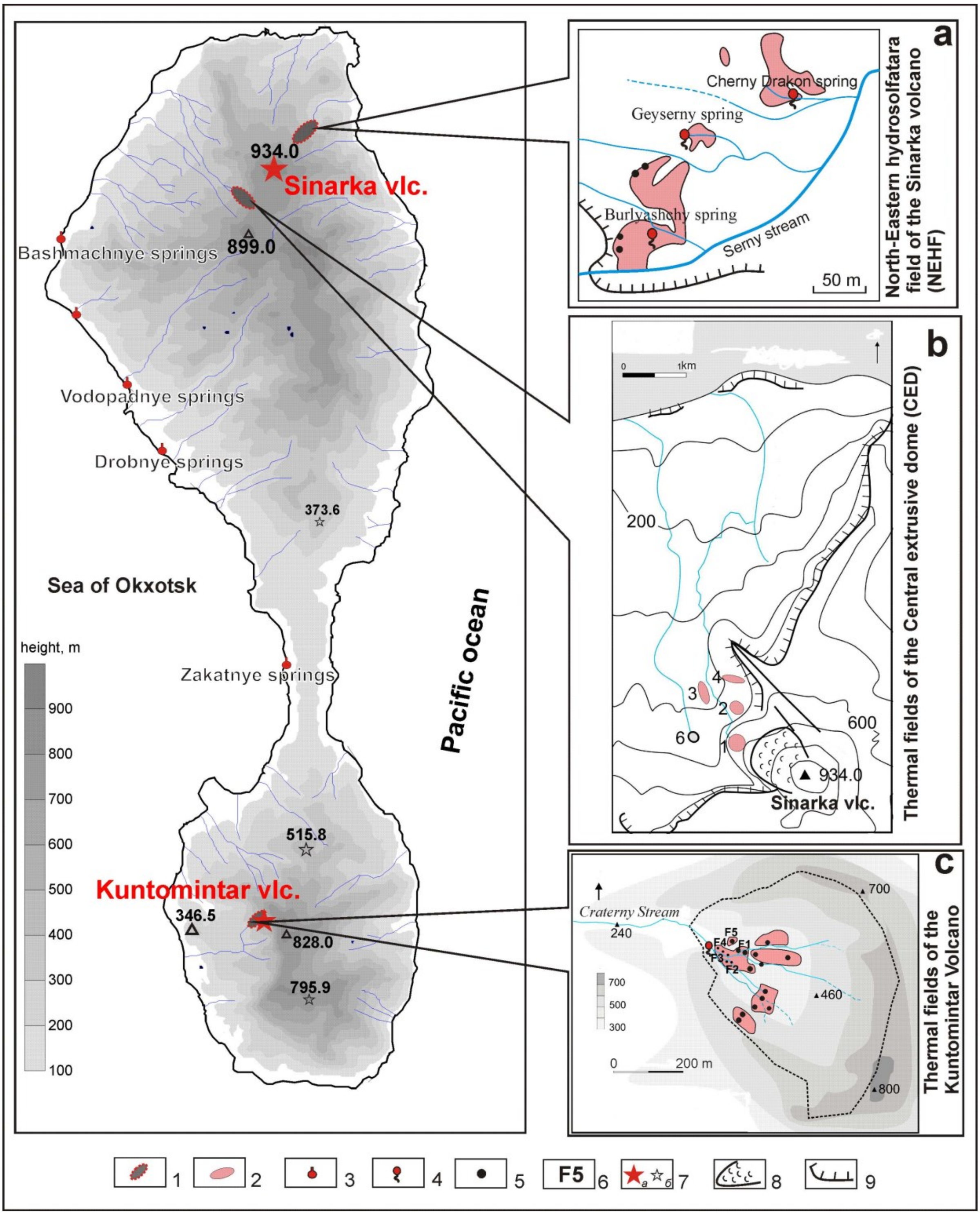

Figure 2. Topographical scheme of the Shiashkotan Island and location of thermal occurrences. (1) thermal fields: a - North-Eastern hydrosolfatara field of the Sinarka volcano (NEHF) (scheme developed by the data of (Zharkov et al., 2011)); b - Central extrusive dome of the Sinarka volcano (CED); c - Kuntomintar volcano crater, (2) thermal sites, (3) coastal thermal springs, (4) individual discharges of thermal waters, (5) steam-gas jets, (6) fumarole No, (7) volcanoes: *a* - active, *b* – extinct, (8) lava flow of the Sinarka volcano extrusive dome, (9) erosion scarps.

3. RESULTS AND DISCUSSION

3.1 Gas geochemistry

Gas and condensate samples presented in the Tables (**Appendix 1 and 2**) were collected from the F5 fumarole of the Kuntomintar volcano on June 24, 2011. To consider the origin of the fumarole gas, triangular diagrams have been developed for the abundances of (mol %) CO_2-HCl-(H_2S+SO_2) (**Figure 3a**) and N_2-Ar-He (**Figure 3b**). The results obtained have been compared using the data on low- and medium-temperature gasses of the Ebeko volcano (Kotenko et al., 2012) and high-temperature gasses of andesitic volcanoes of the Japan (Shinihara et al., 1993) when developing the diagrams.

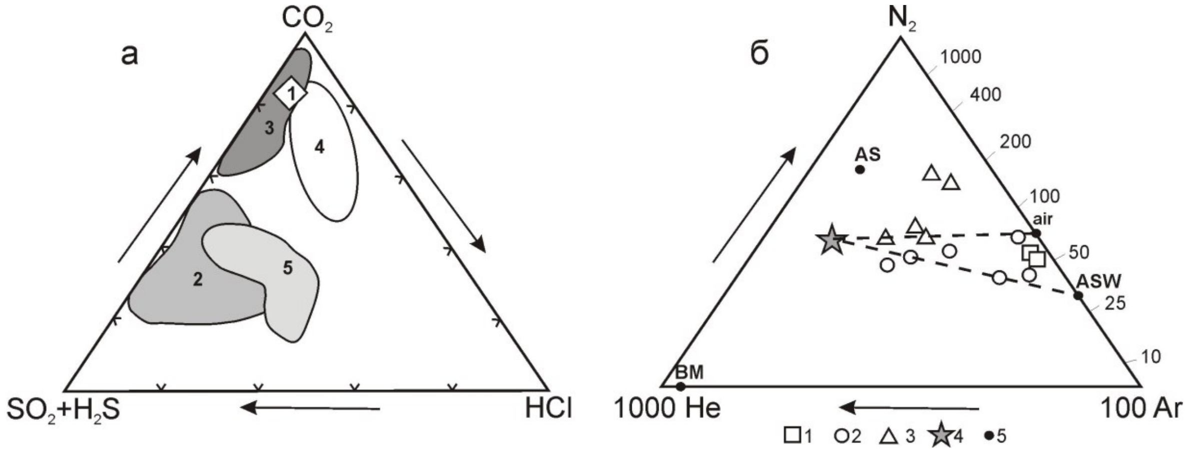

Figure 3. Gas composition diagram within the CO_2-HCl-(SO_2+H_2S) grid (a) and the Giggenbach diagram (b) (Shinihara et al., 1993). (a) Data fields are contoured as follows: (1) Kuntomintar volcano, (2) Ebeko volcano (Iulskoye Fumarole Field), (3) White Island volcano (Giggenbach, 1997), Ebeko volcano (North-Eastern fumarole field, craters), (4) Ebeko volcano (South-Eastern fumarole field), (5) active andesitic volcanoes (Shinihara et al., 1993); (b) – Giggenbach diagram (Shinihara et al., 1993) of the N_2-Ar-He abundance: (1) Kuntomintar volcano; (2) Ebeko volcano (authors' results), (3) high-temperature gasses of andesitic volcanoes in Japan (Shinihara et al., 1993), (4) composition of original volcanic gas reported by *(*Shinihara et al., 1993), (5) peculiar sites showing values typical for: BM – basaltic mantle, AS –andesite subducted, ASW – air-saturated waters (Shinihara et al., 1993).

Though gasses of the Kuntomintar volcano show rather high temperatures, their composition differs from that of high-temperature gasses of andesitic volcanoes (see Figure 3a). Higher abundances of S and Cl have been reported in them. The composition of the water-bearing fumaroles located within the craters of the Ebeko and Bely Ostrov volcanoes is most similar to that of the Kuntomintar volcano gasses.

Contents of N_2, Ar and He in the fumaroles have been studied aimed at evaluating the genesis of the fumarole gasses (Figure 3b). Gas sample compositions are depicted near the N_2-Ar lines within the area of the ratios typical for air or air-saturated meteoric waters. Neither original volcanic gas or the subduction component trend has been observed here, in contrast to the Ebeko volcano gasses and high-temperature gasses of andesitic volcanoes in Japan. N_2/O_2 ratio of 4.5 is somewhat higher than that of the environmental air, which is typical for oxidizing environments (slight deficiency of oxygen compared to nitrogen).

Resulting composition of gasses at the surface is the function of the ascent rate of volatile components and conditions of the migration pathways. Suggested cooling paths are conventionally depicted in the following coordinate grid: gas redox ***ratios*** (log f) – T, °C – lines of equilibrium mineral reactions (natural buffers) (Giggenbach et al., 1990). Redox ratios of the Kuntomintar volcano gasses appeared unusual for the measured surface temperature, all of them corresponding to the lower-temperature conditions typical for the Ebeko volcano gasses (**Figure 4**). Arrows mark the suggested trend towards the lower temperature.

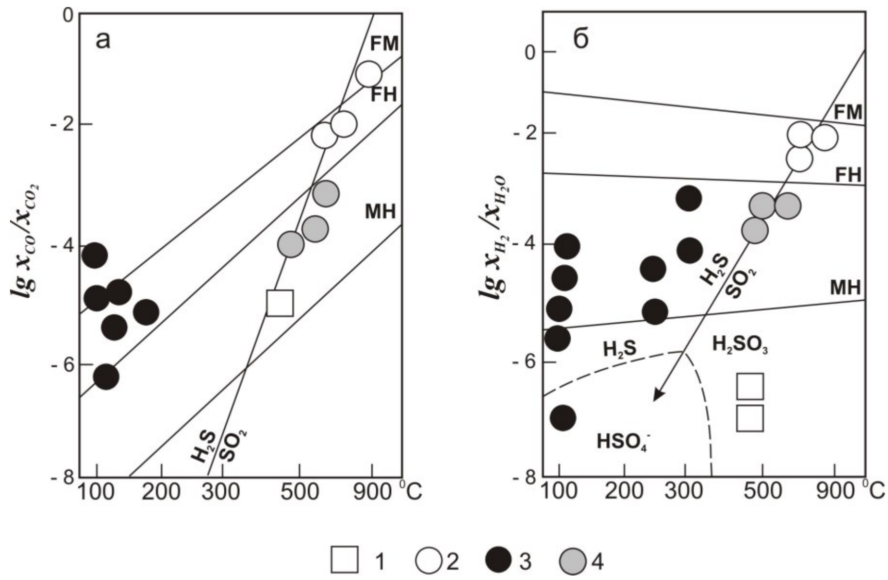

Figure 4. Variations of redox ratios for fumarole gasses and host rocks depending upon surface temperature (1) Kuntomintar volcano, (2) Momotombo, Kudryavy and Augustin volcanos as reported by (Giggenbach, 1987), (3) Ebeko volcano (authors' results), (4) White Island volcano, Papandayan volcano, as reported by (Giggenbach, 1997), Kudriavy volcano (Giggenbach, 1987). Buffer legend: FM – fyalite-magnetite, FH – fyalite-hematite, MH – magnetite-hematite, H_2S-SO_2 – gaseous buffer of the isomolecular coexistence of sulfuric gasses.

Heat-flow calculations were carried out using the Fedotov nomogram (Fedotov, 1982) and observation data on the height of the fumarole jets from the crater. According to our results, the average heat-flow made 40 MWt. In 1970, thermal capacity of steam-gas jets was evaluated as 12 MWt. The difference of the results can be accounted for by the differences in the evaluation methods rather than by the heat-flow intensification.

3.2 Conditions of thermal waters formation

3.2.1 Comparative geochemical analysis of thermal waters

Comparative geochemical analysis of all spring groups has revealed the absence of clear correlation between individual components within the thermal waters of the Sinarka volcano (**Figure 5**). Coastal thermal waters are characterized by linear dependence between major cations and anions with high correlation factors (0.8-0.99). Points in the concentration correlation charts of K-Na, Mg-Na, Cl-Na, SO_4-Na are plotted along the mixing line of seawaters and meteoric waters (see Figure 5), which is the evidence of the determining role of seawaters in the formation of thermal waters discharging within the coastal area of the island. High degree of correlation between the concentrations of certain components in the coastal springs is also indicative of their belonging to a common aquifer.

Plotted are also the data points reflecting the concentration ratios of Cl/B is seawater and meteoric waters, as well as in volcanic rocks typical for the Shiashkotan Island (see Figure 5 c). Okhotsk Sea water near the island contains 3.4 mg/l B and 19128 mg/l Cl (see Appendix 1), Cl/B ratio being 5680. Concentrations of these elements in rainwater is very low. Concentration of B in atmospheric precipitations is below the detection limit, while that of Cl makes 2.13 mg/l. The island is composed mainly of andesites and basalts. Cl/B=30 is common for andesites (A), while Cl/B=65 is more typical of basalts (B) (Arnorsson, Andresdottir, 1995). Virtually all the points plotted in the chart occupy the interposition between the mixing line of meteoric waters with seawaters and the host rock line. The only exception is the fumaroles gas condensate from the Kuntomintar volcano crater where the Cl/B ratio makes 61, which is close to the values typical of the host rocks. The results obtained are indicative of the fact that the chemical composition of thermal waters can be formed due to various degrees of interaction of the host rocks with meteoric and sea waters.

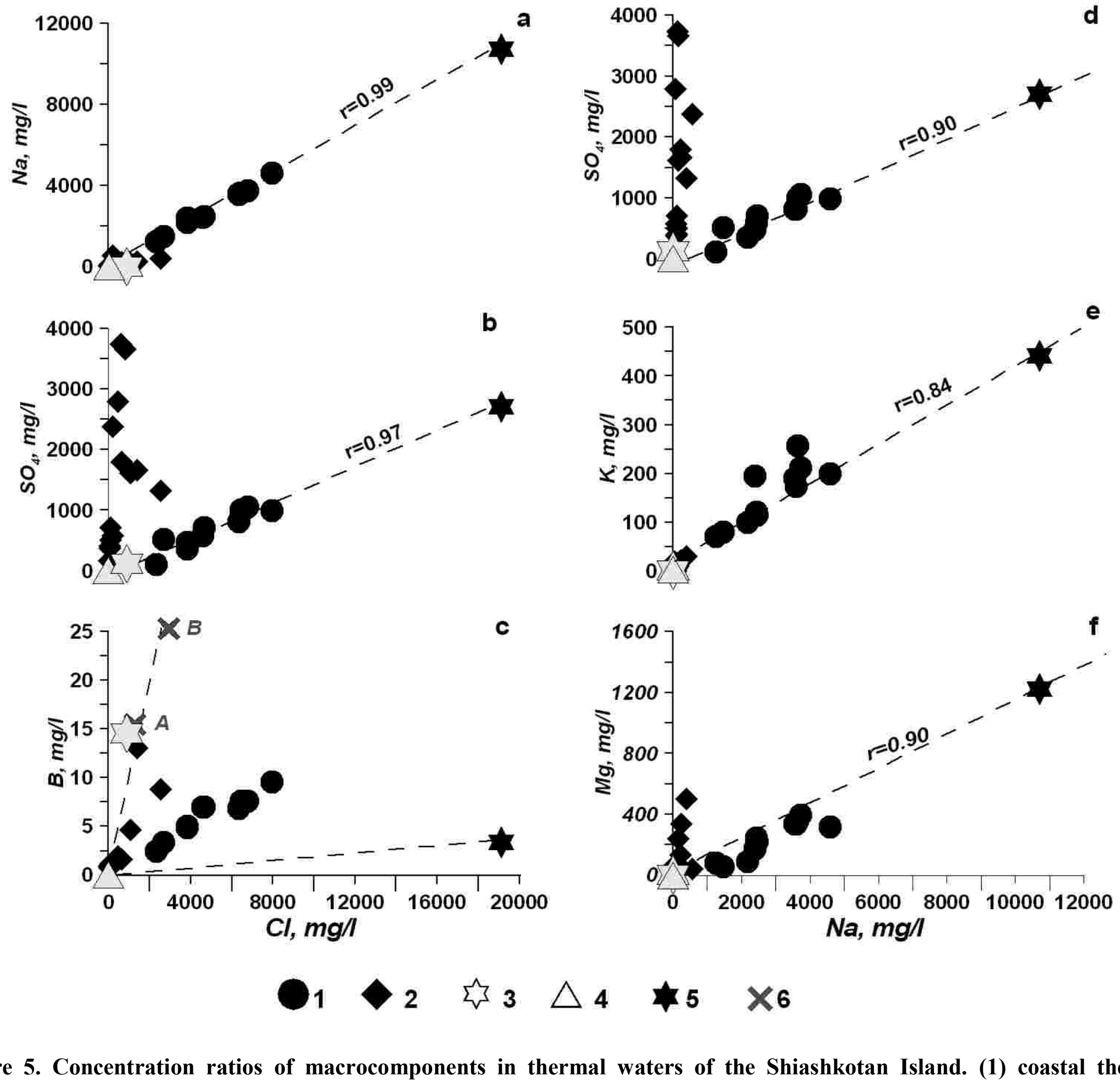

Figure 5. Concentration ratios of macrocomponents in thermal waters of the Shiashkotan Island. (1) coastal thermal springs, (2) thermal springs located at the Sinarka volcano flanks, (3) gas condensate of the Kuntomintar volcano, (4) rainfall, (5) seawater, (6) host rocks: A - andesite, B - basalt.

3.2.2 Temperature regime

Preliminary estimates of abyssal temperatures were made using ion-saline geothermometers. Thermal waters discharging within the island are characterized by low rates and temperatures below 100 ºC. Calculations were made using Na/K- and SiO_2-geothermometers (**Appendix 3**). Abyssal temperatures calculated for the springs of the Sinarka volcano using the SiO_2-geothermometers range 139-186 ^oC for the CED, and 109-112 ^oC for the NEHF, temperatures of the Kuntomintar volcano crater ranging 174-194 ^oC. Temperatures calculated using the Na/K-geothermometers for the coastal thermal springs range from 128 ^oC up to 187 ^oC. Such variations are probably due to the fact that the final chemical composition of Na-Cl thermal waters shows cation ratios corrupted in the result of their mixing with cold groundwaters under near-surface conditions. Abyssal temperatures calculated using the SiO_2-geothermometers for the coastal thermal springs appeared lower than those calculated using the Na/K-geothermometers (Appendix 3). Probably, during the ascent of hydrotherms and in the sites of their surface discharge silica is precipitated and modified from the solution, which results in lower concentrations of dissolved silica acid in the discharge area. Many of the permeable fissures (in dykes and lava bodies) reported at all of the coastal thermal sites are filled with laminated quartz and chalcedony.

3.2.3. Preliminary conceptual models of hydrothermal systems

It is well known that major factors determining the type of hydrothermal systems include the chemical composition of discharging hydrotherms and host rocks, as well as their shallow hydrogeological environments conditioned by the volcanic-tectonic positions and volcanic landscape. Dominating rocks of the island are andesites. Volcanoes hosting the circulating hydrotherms in their depths have complicated edifices of the Somma-Vesuvius type heavily destroyed by seismic-tectonic processes (see Figure 1). Peculiarities of the history of the volcanoes development in the Holocene period conditioned the formation of two different hydrogeological environments in the northern and southern parts of the island, in which two different hydrothermal systems were formed that can be generally described as follows.

North-Shiashkotan hydrothermal system is a typical island-arc hydrothermal system associated with active andesitic volcanism. Surface thermal manifestations of this system extend for 5-8 km over the outflow area and show classic vertical hydrochemical zoning typical for volcanic-arc hydrothermal systems. Projections of ascending hydrotherms on the day surface are asymmetric. Powerful steam-gas activity occurs in the area of the major ascending flow that spatially matches the recent extrusive dome of the Sinarka volcano. Temperature of fumaroles located at the border between the dome and the recent cone averages 100-150 ºC, while the temperature of the dome itself reaches 449 ^oC (Zharkov et al., 2011). Acidic (pH < 4) sulfate-chloride waters with heterogeneous composition, total salinity up to 8 g/l, and temperatures up to 60 ºC discharge over four thermal sites located at the foot of the extrusive dome on the western flank of the volcano. These waters are formed within the aeration zone due to the dissolution of fumarole gasses in the infiltration waters draining the lava flows of the extrusive dome. Multiple steam-gas jets with the temperatures of about 100 ºC, and boiling sulfate and sulfate-chloride springs showing a wide range of pH values and total salinity up to 1 g/l occur at the north-eastern flank of the volcano. The springs are confined to the volcanic-tectonic fault of north-eastern strike (Markhinin, Stratula, 1977). They are also formed in near-surface environments. Emitted from the deep layers of the hydrothermal system, team and gas, mainly CO_2 with admixtures of H_2S, SO_2, and probably some other gasses, ascend along the loose zone to the surface where they get partially absorbed by air-saturated groundwaters. As a result, condensate waters of various chemical composition are formed as considered and described in detail by (Giggenbach, 1997; Arnorsson et al., 2007). Na-Cl thermal waters originating from the deep Cl hydrotherms discharge within the coastal area. Their surface vents are determined by the cross points of faults and dyke complexes of different ages. Common environments of the coastal springs formation are evidenced by their belonging to the same hydrochemical type and high degree of correlation of macrocomponent concentrations. Major source of water supply for the deep-seated hydrotherms are the seawaters penetrating into the system interiors along permeable zones where they mix with the ascending magmatic fluid. As the deep solution migrates up to the surface, it mixes with cold groundwaters, which essentially lowers the temperatures of the hydrotherm vents down to 40-50º C. Thermal and gas supply of the system is provided by huge bodies of cooling rocks located at depths and occupying the feeding channel. Suggested temperature of the deep inner part of the dome body makes at least 500-600 ºC (Stratula, 1969).

Surface manifestations of the Kuntomintar hydrothermal system are constrained by two thermal fields. Major discharge occurs in the forms of powerful steam-gas jets within the crater of a recent pyroclastic cone of the Kuntomintar volcano. Based upon the results of the conducted geochemical researches we can conclude the magmatic origin of the Kuntomintar volcano gasses, since their final composition was formed due to the slow fluid ascent to the surface and its dilution by meteoric waters in the near-surface environments. High surface temperatures of the gasses can be accounted for by the intensive fumarole activity of the volcano. This hypothesis is contributed by a number of increased prognostic ratios of S/Cl, S/C, CO_2/H_2 considered as the precursors of andesitic volcanoes eruptions (Menyailov, 1976; Kotenko et al., 2012), as well as by the discovery of a new thermal site.

4. CONCLUSIONS

Results of the geochemical researches conducted allow modifying the conventional knowledge about the conditions in which thermal waters are formed and discharged at the Shiashkotan Island. Previously reported (Markhinin, Stratula, 1977) was the hypothesis suggesting that the springs located within the coastal area of the island had been formed due to the near-surface mixing of the ascending overheated flow formed immediately beneath the discharge area with infiltration waters. Our results have proved that hypothesis invalid. Thermal waters discharging over the coastal area cannot exist independently; they are an integral part of a hydrothermal system. Summarizing the results available, Corbett and Leach (1998) reported the features of island arc hydrothermal systems. They pointed that due to insufficient hydrostatic pressures in the deep Cl reservoir, ascending neutral Na-Cl therms would never reach the surface above the zones of ascending flows. The relief of volcanic regions above the ascending flow zones is split showing steep slopes. Reservoir pressure (gas plus hydrostatic pressure of high-temperature hydrotherms) is therefore not high enough to overcome the inhibiting pressure of the surrounding cold groundwaters. As a result, hydrotherms flow laterally 5-10 km down the slope reaching the lower topographic levels where their discharge is controlled by the sea level. Similar situation is observed in the northern part of the Shiashkotan Island where the North-Shiashkotan hydrothermal system is located. High degree of correlation of macrcomponent concentrations in the waters of the coastal thermal springs attests to their association to a common aquifer. Therefore, the Zakatnye springs are confined to the North-Shiashkotan hydrothermal system instead of the Kuntomintar system as was previously suggested (Barabanov, 1976).

Though similar in the Somma-Vesuvius type edifices (Gorshkov, 1967), matter composition and intensive summit solfatara activity, the two volcanoes considered underwent different final stages of their formation. In the case of the Kuntomintar volcano, the final stage was associated with the caldera formation, while the extrusive dome was formed on the Sinarka volcano. Specific development of each volcano led to setting different hydrogeological and geological environments in which two different hydrothermal systems were formed within the interiors of these volcanoes. The North-Shiashkotan hydrothermal system shows typical hydrochemical zoning. The Kuntomintar system is of local type, its surface manifestations being constrained by two thermal fields. High surface temperature of gasses and a number of high prognostic ratios (S/Cl, S/C, CO_2/H_2) in the gas composition are indicative of possible intensification of the volcano fumarole activity. The results obtained during our study are preliminary. Further researches are required aimed at defining the genesis of thermal waters discharging within the Shiashkotan Island.

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APPENDIX 1

Chemical composition of Shiashkotan thermal waters

	Sampling site	Hydrochemical type	T, °C	pH	Eh mV	SEC µS/cm	H_4SiO_4 (H_2SiO_3)	H_3BO_3 (HBO_3)	M, g/l	Cl^-, mg/l	HCO_3^-, mg/l
Kuntomintar volcano (crater)	Craterny stream head	Al-Ca-SO_4	18.4	2.42	265	6580	198.90	2.04	5.41	312.4	
	Thermal spring at the Craterny stream bank	Al-Ca-SO_4	64.5	2.35	311	3380	506.80	10.88	5.43	461.5	
	Fumarole gas condensate (F5 fumarole)	Ca-Cl		2.30	310	10080	2.32	80.92	1.30	887.5	
Sinarka volcano (NEFF)	Thermal site 4*	Ca-Na-Mg-SO_4	25.0	4.60	n/a	n/a	(84.95)	(7.00)	1.49	95.8	1.80
	Geyserny spring*	Ca-Na-SO_4	78.0	7.60	n/a	n/a	(167.31)	(5.00)	1.09	68.9	153.72
	Burlyashchy spring*	Na-Ca-SO_4	90.0	3.00	n/a	n/a	(127.75)	(4.00)	0.83	41.5	n/a
	Black Dragon Spring**	Ca-Mg-SO_4-Cl	93.1	7.10	n/a	n/a	(104.00)	-	1.34	206.0	91.50
Sinarka volcano (CED)	site 4**	Ca-Mg-SO_4-Cl	38.1	2.80	n/a	n/a	(179.00)	-	4.29	1028.0	
	site 1	Mg-Ca-Cl-SO_4	51.2	2.67	279	8040	456.80	48.96	6.20	2538.2	
	site 2	Ca-Mg-SO_4-Cl	37.6	3.21	234	4610	315.60	25.80	4.15	1065.0	
	site 3	Mg-Ca-Cl-SO_4	42.6	3.00	271	5750	293.60	21.76	4.74	1384.5	
	Aglomeratovy stream, below the thermal sites	Ca-Mg-Cl-SO_4	21.3	3.38	211	3180	179.20	14.30	2.29	681.6	
Coastal springs	Zakatnye springs	Na-Cl	53.4	6.03	52	12600	120.10	27.20	7.64	3834.0	337.94
	Zakatnye springs 2	Na-Cl	30.0	5.94	63	8310	111.83	0.28	3.06	1420.0	289.70
	Vodopadnye springs	Na-Cl	55.6	6.88	9	12850	269.40	65.28	8.84	4657.6	112.00
	Vodopadnye springs 2	Na-Cl	63.8	6.30	47	12660	269.40	62.56	8.69	4586.6	129.30
	Drobnye springs	Na-Cl	43.0	6.27	47	18260	201.76	42.16	12.88	6780.0	225.70
	Drobnye springs 2	Na-Cl	43.4	6.66	21	17760	219.20	42.16	12.43	6461.0	208.60
	Bashmachnye springs*	Na-Cl	74.0	6.61	н/о	н/о	(175.80)	-	4.35	2303.6	106.14
	Bashmachnye springs 2*	Na-Cl	71.0	6.35	н/о	н/о	(246.40)	-	7.20	3815.5	80.50
rainfall		K-Na-Ca-SO_4-Cl	5.0	4.86	124	38	0.92	<0.28	13.73	2.1	
Okhotsk Sea		Na-Cl	4.0	7.10	n/a	n/a	n/a	19.80	34.87	19127.7	134.20

Chemical composition of Shiashkotan thermal waters (end)

	Sampling site	HSO_4^- mg/l	SO_4^{2-} mg/l	H^+ mg/l	Na^+, mg/l	K^+, mg/l	Ca^{2+}, mg/l	Mg^{2+}, mg/l	Fe^{2+}, mg/l	Al^{3+}, mg/l	Fe^{3+}, mg/l
Kuntomintar volcano (crater)	Craterny stream head	566.48	3269.8	6.25	63.64	1.95	412.8	26.75	n/a	355.50	195.30
	Thermal spring at the Craterny stream bank	667.70	2795.0	8.65	63.94	1.95	364.7	29.20	<0.05	337.50	181.40
	Fumarole gas condensate (F5 fumarole)	97.00	122.9	24.10	0.72	1.56	76.2	4.86	<0.05	<0.30	<0.05
Sinarka volcano (NEFF)	Thermal site 4*		708.9		104.75	5.59	174.4	49.61	-	-	-
	Geyserny spring*		405.5		100.35	9.00	122.0	25.96	-	-	0.50
	Burlyashchy spring*		379.6		87.17		71.6	18.36	2.50	-	2.00
	Cherny Drakon Spring**		580.0		84.00	12.00	217.0	47.40	0.80	-	0.10
Sinarka volcano (CED)	site 4**		1960.0	5.00	175.00	11.20	536.0	304.00	0.10	50.00	89.60
	site 1	216.30	1321.9	5.15	385.00	29.80	545.1	501.00	<0.05	49.14	106.02
	site 2	114.46	1612.8	2.25	159.9	10.56	513.0	238.30	<0.05	73.80	14.10

	site 3	165.70	1660.8	3.10	250.01	21.20	489.0	338.00	<0.05	43.52	68.00
	Aglomeratovy stream, below the thermal sites	61.11	784.3	2.35	111.80	4.10	272.5	136.20	<0.05	29.34	12.24
Coastal springs	Zakatnye springs		474.2		2398.90	195.40	80.2	170.24	<0.05	<0.30	<0.05
	Zakatnye springs 2		182.4		839.04	35.88	150.3	32.83	<0.05	<0.30	<0.05
	Vodopadnye springs		711.4		2449.50	114.10	240.5	220.10	<0.05	<0.30	<0.05
	Vodopadnye springs 2		583.7		2433.40	120.12	260.5	245.60	<0.05	<0.30	<0.05
	Drobnye springs		1058.0		3730.00	211.40	240.5	394.00	<0.05	<0.30	<0.05
	Drobnye springs 2		1003.2		3638.60	257.40	240.5	355.10	<0.05	<0.30	<0.05
	Bashmachnye springs*		109.4		1246.95	70.00	245.0	8.05	n/a	n/a	n/a
	Bashmachnye springs 2*		355.4		2273.40		249.3	91.00	n/a	n/a	n/a
rainfall			6.2		1.30	2.34	0.8	<0.12	<0.05	<0.30	<0.05
Okhotsk Sea***			2704.4		10699.6	440.80	440.9	1220.9	n/a	n/a	n/a

Note. n/a – not analyzed, - – below the detection limit, Data by: *- (Markhinin, Stratula, 1977), **- (Zharkov et al., 2011), *** (Barabanov, 1976). Water specimens sampled in 2011have been analyzed in the Analytical Center (AC) of the IVS FEB RAS. Analyst – A.A. Kuzmina.

APPENDIX 2

Average composition of the fumarole gas of the Kuntomintar Volcano 24.06.2011, mol.%

T °C	H_2O	without H_2O											S/Cl	S/C	CO_2/H_2
		CO_2	H_2S	SO_2	HCl	CO	CH_4	H_2	N_2	O_2	Ar	He			
480	98.24	80.309	9.298	7.812	0.415	0.00014	0.0012	0.0017	1.743	0.391	0.028	0.00017	37.48	0.21	49969

Note. Gas sample analyses were carried out in the AC of the IVS FEB RAS. Analysts – V.N. Shapar', I.F. Timofeeva.

APPENDIX 3.

Measured and calculated deep temperatures of the Shiashkotan thermal waters

Sampling site	T, °C	SiO_2-Q		SiO_2-Chl		Na/K	Na/K	Na/K
		F	A	A	F	N	T	A
Zakatnye springs	53.4	118	117	93	91	187	183	175
Drobnye springs	43.0	142	141	119	123	160	163	143
Drobnye springs 2	43.4	146	145	123	128	176	184	162
Vodopadnye springs	55.6	157	156	134	143	147	145	128
Vodopadnye springs 2	63.8	157	156	134	143	151	150	133
site 1 (CED)	51.2	186	186	167	185			
site 2 (CED)	37.6	165	165	144	155			
Site 3 (CED)	42.6	161	161	139	149			
Thermal spring at the Craterny stream bank	64.5	193	193	174	194			
Cherny Drakon spring (NEFF)	93.1	112	110	109	111			

Note. Authors of geothermometers: F - Fournier, (1977); A - Arnorsson et al., (1983); N - Nieva and Nieva, (1987); T - Tonani, (1980)