Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Hydrogeology and Hydrodynamics of North-Paramushir Geothermal Area (Kuril Islands)

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Keywords: geothermal, hydrothermal ore-forming processes, feed areas, hydrodynamic.

ABSTRACT

We have studied the macrocomponent composition of natural waters and reconstructed the hydrochemical zoning and dynamics of the surface and underground waters within the North-Paramushir hydrothermal-magmatic system. We have studies the areas of feeding and discharge of pressure waters of the upper water-bearing horizonts and complexes restricted to the isometric geological blocks 1.5-2 to 3.5-5 km across and to the ruptured tectonic structures of local and regional types. It is shown that in the Paramushir Island northern part all water types characteristics of the hydrothermal systems, related with the island-arc andesite volcanoes, are present. The composition of hydrotherms and gases is of a great meaning for the formation of deep-level flow structure and the evolution of hydrothermal and magmatic processes in the interior of North-Paramushir geothermal area. The availability of a great of carbon dioxide, hydrogen and other gases creates conditions for a high dynamics of physical-chemical and structure-forming processes.

1. INTRODUCTION

The North-Paramushir geothermal area has attracted researchers for many decades (Nekhoroshev, 1960; Zelenov, 1972; Menialov et al., 1992; Rychagov et al., 2001). The interest of this area is conditioned by its insular position at the interface of oceanic and continental crust, by a great thickness of the system, by the presence of the active andesite volcano Ebeko in the central part and by the complex structure of the system's feed zone. The North-Paramushir hydrothermal-magmatic convective system under study is an intrusive-volcanogenic complex, long-evolving (since Paleogene up to now) and large (a volume of its host rocks ≥ 700 km^3) geological structure, now being in an infancy stage of island arc. A magmatic source drives heat and material transfer, the origin of which may be both primary (generation of melts at the upper mantle level – a nearsurface magmatic center – a subvolcanic body), and secondary (heat release in process of exothermic chemical reactions) (Belousov et al., 2002). The North-Kuril geothermal deposit is located in the eastern section of the hydrothermal-magmatic system. Estimated geothermal resources of the deposit exceed 100 MW of electric capacity. Apart from geothermal processes, modern mineral- and ore-formation is of a great interest: deep drilling showed deep-level formation of gold-polymetallic mineralization, and, possibly, the genesis of a copper-porphyry type of mineralization (Rychagov et al., 2002). Geological, hydrodynamic, and geochemical studies allowed development of geological-geochemical and structural-hydrodynamic models of the North ore-generating hydrothermal-magmatic system that are of great importance for understanding the process of modern hydrothermal ore formation and for orientation of prospecting works to hydrothermal and mineral resources.

2. GENERAL GEOLOGICAL-HYDROGEOLOGICAL DESCRIPTION OF THE NORTH-PARAMUSHIR HYDROTHERMAL-MAGMATIC CONVECTIVE SYSTEM

The Paramushir Island is a relatively elevated block of the earth's crust and is considered a southern continuation of the South Kamchatka horst (Aprelkov, 1971). The northern end of the island is composed of volcanogenic-sedimentary, intrusive and volcanic erupted rocks of Upper-Miocene to modern age and of glacial deposits (Rychagov et al., 2001). The basement consists of tuffs and tuffites of the Okhotsk suite of Upper-Miocene-Lower-Pliocene age. Thickness of the suite is within a range of 1400 to 3000 m. Tuffs and tuffites of 900 to 1000 meters thick Oceanic suite of Middle-Upper-Pliocene age overlie the Neogene deposits. Rocks of Okhotsk and Oceanic suites are intruded by sills, dykes and other subvolcanic bodies of andesite-basalt and basalt composition. Large eroded subvolcanic bodies (for instance, Aerodromnoye Plateau) are up to 2500-4500 meters across. The contacts of these bodies with host rocks consist of breccias and large-blocks. Contact zones ranging from 1-5 to 10-30 m and more are visible. Subvolcanic bodies are of interest as possible analogs of modern intrusive bodies, feeding a hydrothermal-magmatic system. Lavas of andesites and basalts of Upper-Pliocene-Holocene age constitute a series of thick flows. Three groups of volcanoes are distinguished, that form the Vernadskogo Ridge which is a North to South extended volcanic-tectonic structure. There is an active volcano, called Ebeko. It is known to have 5 cycles of activity in historical time in 1793, 1895, 1934-38, 1967-71 and in 1987-91. (Menialov et al., 1992). The last eruptions were phreatic. Currently, the volcano is in a stage of intensive fumarolic activity. The Krasheninnikov volcano also shows some steam-gas activity. The central part of the North-Paramushir hydrothermal-magmatic system is localized in a concentric morphotectonic ring structure, formed at the intersection of a north-northeast and west-northwest tectonic zones (Fig. 1). A Negative gravity anomaly was identified within the Ebeko volcano area, which is attributed to a lesser density of rocks, forming a vertical cylindrical body of oval section with a size of ~ 2 x 1 km. Rocks were altered to opalites and argillizites propagating to a depth of around 1 km. The reference geological section of the hydrothermal-magmatic system is composed of four complexes of rocks (Rychagov et al., 2002). The bottom of the section (2500-1700 m) is composed of lithocrystalloclastic psepho-psammitic tuffs of andesite-basalt composition and intrusive tuffs (breccias), forming a block-breccia mantle of a large diorite body. The middle strata (1700-960m) are lithocrystalloclastic tuffs of andesite composition, brecciated in the upper part of deposits. The upper volcanogenic-sedimentary strata (960-140 м) consist of alternating bands of psepho-psammitic and aleuro-pellitic tuffs and tuffites; the bottom of the strata is dominantly manifested with tuffs; the upper part is mainly composed of tuffites containing relics of marine microfauna. Holocene age lavas of andesite composition overlay the section. The main portion of the middle strata acts as an aquifer; volcanogenic-sedimentary rocks have water-confining properties. It is suggested that the block-breccia mantle of the diorite body hosts the most high-temperature and, possibly, ore-bearing therms. Between the middle and upper strata there is a higher permeability zone including a thick vapor-dominant system on the upper and lower borders of which ore geochemical barriers are formed. Complex of sulfide and oxide minerals is formed in rocks; native metals, their alloys and intermetallic compounds are deposited in fractures and pores.

In northern part of Paramushir island the following tipes of waters are represented **(Fig. 1)**. Ultra acidic waters (pH 0-3) are discharged on Ebeko volcano. The waters are shaped at the expense of merging magmatic gases with meteoric waters. Acidic waters (pH 3-5.5) have compound cationic composition. They are shaped at the expense of interaction of underground waters with metasomatites. The neutral waters (pH 5.5-7.5) have speckled cationic composition. Waters are shaped at the expense of atmospheric precipitation. The alkaline waters (pH 7.5-8) are detected by drill-holls. It is deep-level chloride-sodium hydrotherms.

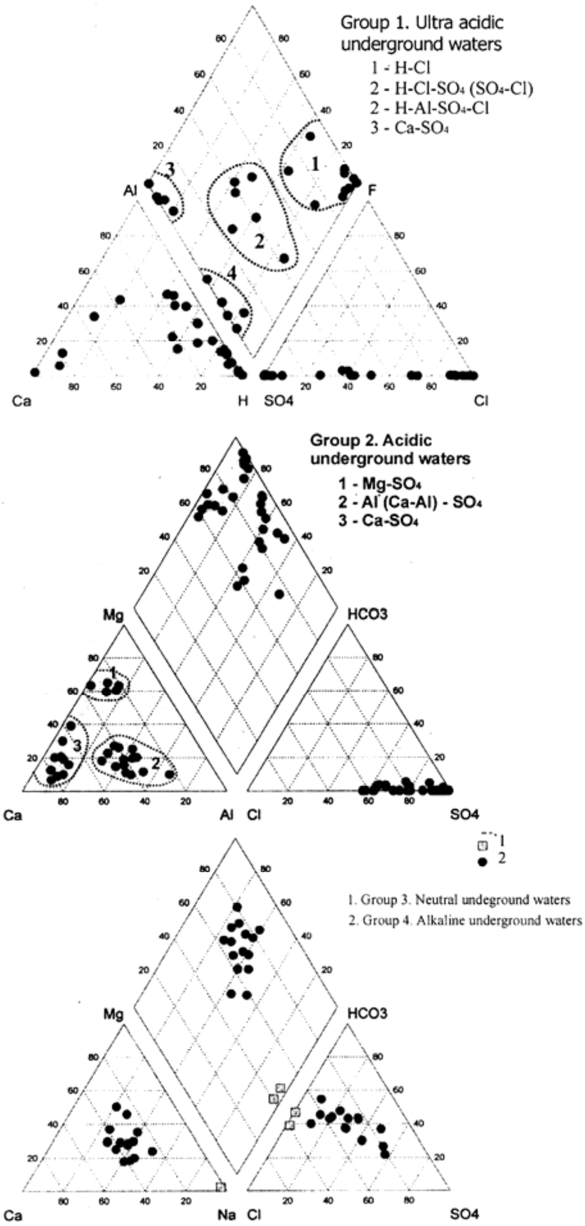

Figure 1: Chemical composition of different water types of North-Paramushir area.

Chloride-sodium deep-level hydrothermal fluids are typical waters for the lower water-bearing complex of the Kuril-Kamchatka region. Chloride-sulfate, sulfate and hydrocarbonate-calcium hydrotherms are formed in a zone of mixing of deep-level and meteoric waters. Sulfur discharge centers of deep-level hydrotherms are low-thermal chloride-sulfate waters with pH 3.5 – 5.5. Sea waters, penetrating 2.5 km inland to an axis zone of the Vernadskogo Ridge, significantly influence the composition of the hydrothermal fluids. In all, hydrotherms are formed by mixing of meteoric and sea waters, volcanic and hydrothermal gases and deep-level fluids.

3. HYDRODYNAMIC CHARACTERISTICS OF THE NORTHERN END OF THE PARAMUSHIR ISLAND

There are various approaches for determining input to hydrothermal systems; the water balance method is simplest. The method includes determination of moisture input and discharge over any period of time for the area under study. Setting up a simple equation of water balance for a separate area is the main difficulty. The best solution to this problem is to study a multiyear water balance (Kudelin, 1960). In this case the area is divided into balance sections corresponding to river basins. An equation of water balance for a separate area over a multiyear period is of the following form:

$$\pm W = X - Y - Z, \text{ where} \quad (1)$$

X – calculated normal annual precipitation; Y – calculated normal annual run-off; Z – calculated normal annual evaporation; ±W- normal annual infiltration into deep water-bearing horizons within the feed zone, or calculated artesian run-off within the discharge zone, or difference between them.

3.1. Precipitation

Cold waters of the Okhotsk Sea and of the Kuril Current shape the climate of the Paramushir island. The region is characterized by cold winters with frequent blizzards and chilly damp foggy summers. An average annual precipitation in the town of Severo-Kurilsk is 1795 mm (Table 1). But these data are correct for the meteorological station altitude (23 m above the sea level), whereas the area under study occupies territory with absolute points of 0 m to ~ 1150 m (the Ebeko volcano). Using an altitude distribution correction factor ≈ 1.7, derived for the Pauzhetsky area (the South Kamchatka), situated short of the Paramushir island (Vakin, 1968), we can calculate normal annual amount of precipitation in the North Paramushir - 3123 mm.

3.2. Evaporation

Evaporation in natural conditions is an intricate process depending on many meteorological factors: humidity, ambient temperature, wind velocity etc. Also, relief, ground water occurrence, structure and composition of soil-vegetation cover greatly influence evaporation process. Since no special study of evaporation in the area was conducted, and meteorological data refer only to the urban areas, we will estimate evaporation by a graphic extrapolation method. An average annual evaporation value is 381 mm.

3.3. River run-off

The area under investigation occupies an area of 215 km^2. Volcanic, tectonic, intrusive and denudation processes by permanent and temporary water courses play the major role in the formation of the area's relief. Rivers of the area belong to the basins of the Okhotsk sea and Pacific ocean. The Vernadskogo ridge The north-east rivers are an exception: they have flat lengthwise profiles and relatively tranquil flows. Totally, there are more than 20 distinct water courses 3 to 15 km long with many small inflows. Temporary water courses with episodical run-offs are widely spread on the slopes of volcanoes. Water collection for rivers takes place by means of atmospheric precipitation and underground water discharge. Surface volcanics are mainly highly-permeable rocks, through which surface run-off goes underground.

3.4. Description of balance sections

For run-off calculation purposes, the area was divided into three large balanced sections (?) including several lesser ones. Section selection criteria included hydrological, geographical and other aspects, and also a level of study of the area's river basins. Since there are no water gauge stations on the island, hydrometric works were being done during summer mean water level except for rivers near the town of Severo-Kurilsk where regimen monitoring was organized in 2001. Normal annual runoff is the main estimated parameter of river run-off (an average annual run-off over multiyear period). Where there is a lack of field work data, the methods of approximated determination of normal run-off are used. The following formula of Kritsky (Solomentsev, 1961) can be applied for the area in question:

$$ŋ =11/(d^3\sqrt{d}+11),$$

where ŋ- normal annual run-off, mm, d –filling deficit (See table 1)

$$ŋ =11/(1.54^3\sqrt{1.54}+11)=0.708$$

Proceeding from an amount of precipitation, normal annual run-off is determined for the separate river basin: Y=X * 0.708. Y=3123 * 0.708 = 2271 mm

In this manner, all terms of the water balance equation were derived; the precision of the determinations is sufficient for a pre-assessment of the amount of infiltration feeding the underground waters of the North-Paramushir hydrothermal-magmatic system. According to formula1, W = 3123-2271-381=471 mm. W has a positive value, therefore underground water refilling in the area averages 471 mm a year. For the purpose of a detailed study of water balance on the development territory of the hydrothermal-magmatic system, calculations were done for all the river basins of the identified balance sections.

3.4.1. The eastern section

The eastern section is of a special interest because its interior hosts the presumed North-Kuril geothermal deposit. Water gauge stations were set up in estuary zones for regimen monitoring of first-order water-courses. Seeing that amount of precipitation in the northern end of the Paramushir island over the last hydrological year did not differ much from the mean annual value over the whole monitoring period, data on average annual river discharge can be used as the multiyear average. **Table 2** shows the results of water balance calculations. Infiltration values for all the rivers are negative. But this increment is very low in the Kuzminka river basin: water balance calculations reveal neither absorption of atmospheric precipitation for feeding deep-level water-bearing horizons, nor significant discharge of underground waters, which allows this section to be considered an underground pressure area. Significant discharge centers of deep-level water-bearing horizons were determined by water balance calculations in basins of the rivers of Nasedkina, Ptichiya, Matrosskaya and Snezhnaya. Moisture excess in these sections is 9% (the Snezhnaya river) and 26% (the Ptichiya river) of normal annual precipitation values. Infiltration in the basin of the Gorodskaya river has also a negative value, but water excess is caused both by deep-level pressurized water discharge and by discharge of upper water-bearing horizons.

3.4.2. The Northern and Western sections

In view of episodical hydrometric measurements at these sections, a value of run-off was determined by means of empirical formulas, mentioned above. The other parameters were determined in the same manner as for the Eastern section (See Table 2). Infiltration (±W) all over the territory ofthe Northern section has a positive sign, and a water balance equation is of the form X=Y+Z+W, which is typical of river basins, located within an underground water feed area. The calculations show that feeding of deep water-bearing horizons takes place with an equal intensity in all the river valleys (15-17% of normal annual precipitation). The lack of data on river profiles does not allow the delineation of feed zones at this section. However, the field studies we conducted in summer and fall of 2001, and literature data (Opit Kompleksnogo…, 1966) indicate numerous vents of ground waters in downstream of the Savushkina, Zelenaya etc. rivers on the contacts of lava flows and modern alluvium. Based on this data, **Fig. 2** shows the discharge zone of upper water-bearing horizons of the Northern water- balance section. A negative increment of water balance at the Western section is observed in the Yurievaya and Gorshkovaya river basins. Moisture excess is due to numerous thermal water vents there. Infiltration is positive on the rest of the territory and, consequently, the basins of the Lozhkina, Lozovaya, Pereturpit' and Burnaya rivers are situated in the underground water feed area; feed intensity of water-bearing horizons is practically equal (13-16% of normal annual precipitation).

4. WATER FLOWS WITHIN THE STRUCTURE OF THE HYDROTHERMAL-MAGMATIC SYSTEM

Geological structure of the northern end of the Vernadskogo ridge is manifested by two large geological blocks with a size of 9 to 12 km across **(Fig. 2)**. The first (Northern) irregularly-isometric block with center near the Ebeko volcano is composed of rocks of andesite composition and hosts several paleocalderas. The second (Southern) block is manifested by an isometric ring structure with dual center in vicinity of the Bogdanovich and Krasheninnikov volcanoes and composed of rocks of more basal composition (to olivine basalts). These structures of the first order host morphotectonic blocks 2-5 km in size, the main of which are shown in thefigure. It is clearly obvious that flows of underground and ground waters are radially directed relative to large structures, and in a certain manner interact with small blocks of rocks. According to petrological data and morphotectonic criteria, the Southern ring block was created by intrusive-tectonic tensions at depths of 2-3 to 7-9 km. This means that there at a depth of more than 2 km (the upper edge), one should expect the presence of a large source of heat and deformational tensions – a magmatic center or zone of rocks, heated up by chemical reactions (Belousov et al., 2002). This suggestion is supported by hydrochemical data, derived during a recent Kuril expedition of the Institute of Volcanology: chloride – chloride-sulfite thermal waters are discharged in the headstream of the Nasedkina and Ptichiya rivers. A geological block having a diameter of 5 km and located on the southern border of the area is the prospect; the contours of the block are traced by volcanic cones, explosion craters and hot springs. Largely, annular morphotectonic blocks and radial to them zones of discontinuous tectonic faults control main water flows and volcanic manifestations of Holocene and modern age. Based on these data and reference generalizations, we present a flow structure of gas and water fluids within the section of hydrothermal-magmatic system.

The principal structure of fluid flows and formation of physical-chemical zones in the interior of the North-Paramushir hydrothermal-magmatic ore-forming system can be presented as follows **(Fig. 3)**. Largely, we can conditionally denote 4 zones: conductive heat transfer zone, convective heat transfer zone, zone of two-phase hydrotherms and phreatic zone. Conductive heat transfer is characteristic of intrusive bodies, mainly composed of non-fractured rocks. But for volcanogenic-sedimentary rocks, enclosing intrusion, for near-contact zones and above-intrusion complex, convective heat transfer is typical. A two-phase zone occurs at shallow depths and within hydrotherm overflow zone, in which steam pressure does not exceed the hydrostatic pressure, what causes separation of steam and gases (mainly CO_2 and H_2S in subordinate quantity) from hydrothermal flows. Boiling may take place at a depth of 2 km and even deeper in some systems (Bogie et al., 1987). Dissipation of boiling zone at small depths leads to the formation of bicarbonate solutions with moderately low pH. Phreatic or saturation zone consists of several flows of underground waters, located above chloride-sodium waters. Carbon dioxide, released from hydrotherm boiling zones, is absorbed in near-surface therms. Nearsurface degassing of CO_2 leads to the formation of neutral bicarbonate waters and precipitation of travertines. Silica acid largely affects the formation of hydrothermal flows and the geological structure of hydrothermal-magmatic systems. Precipitation of colloid silica, caused by boiling of deep hydrotherms within fracture zones, promotes the formation of an upper confining layer and ore geochemical barriers on the borders of vapor dominant systems. Carbon dioxide together with water are the main components of the volatiles. A magmatic origin of interior CO_2 is supported by carbon isotopic data and by calculations. It is established, that volcanoes such as Ebeko, emit 10-100 times more CO_2 by means of fumarolic activity than by surface-effused magma (Menialov et al., 1992). In this respect, it is assumed that the largest portion of CO_2 is degassed from intrusive magma. This is conditioned by the low solubility of carbon dioxide in silicate melts under moderate to low pressures. Therefore, carbon dioxide is one of the main components of deep-level magmatic fluids; it is capable ofaccumulating in the form of bubbles in the upper sections of magmatic reservoirs; it can be a transport phase for other volatiles; it can sustain a permanent efflux regime for thermal surface manifestations (Allard, 1992). Hydrogen makes a significant portion in steam-gas mixture. Gradual compaction of the upper water-confining horizon by silicification and argillization of rocks may cause an increase of hydrogen concentrations in the near-surface horizons of the system and temperature increase of steam-hydrotherms (such a fact was established by an example of the Baranskogo hydrothermal-magmatic system (Rychagov et al., 1993)). The high solubility of H_2S, SO_2 and other gases in water causes a still greater increase of H_2 and CO_2 concentrations due to their low solubility in hydrotherms. Hydrotherms get overheated thus creating conditions for phreatic explosions. Power of explosions gets increased by degassing of CO_2 from a depth of 2.2 km. Gas degassing level gets lower at that due to steam-gas lift thus creating conditions for intensive ingress of atmospheric air to the system's interior. Owing to this, air-hydrogen mixture is formed, capable of combustion and powerful explosions. Intensive effusions and explosions of gases cause vacuum above the magmatic center. The vacuum induces degassing of melts to a large depth and rise of gas-saturated magma to higher horizons. According to our estimates, degassing of material by gas lift goes to a depth of 4-5 km. Just these gas-chemical and hydrodynamic processes can explain the presence of a big amount of explosion craters along the Vernadskogo ridge (Fig. 1) and present-day phreatic activity on the Ebeko volcano. The rise of gas-saturated magma and its interaction with descending flow of hydrotherms causes additional boiling of fluids and causes the formation of high-temperature mineralized ore-bearing fluids, which play a great role in all stages of the evolution of the North-Paramushir hydrothermal-magmatic convective system.

5. CONCLUSIONS

The performed investigations allow one to make the following conclusion. On the whole, the northern end of the Paramushir island is situated in the feed zone of underground waters. Underground water reserves are annually refilled in an amount of about 471 mm, what makes 15 % of the total amount of atmospheric precipitation. The detailed water-balance calculations showed two large underground water discharge zones, situated in the Yurievya, Nasedkina, Ptichiya, Matrosskaya and Snezhnaya river basins. The detailed water-balance calculations showed the underground water pressure area in the Kuzminka river basin. The identified areas are delineated in draft form and need to be specified with the Eastern water-balance section's discharge area extending beyond the investigated area. The composition of hydrotherms and gases is of a great meaning for the formation of deep-level flow structure and the evolution of hydrothermal and magmatic processes in the interior of the North-Paramushir system. The availability of a great amount of carbon dioxide and hydrogen creates conditions for a high dynamics of physical-chemical and structure-forming processes. The work has been done with a financial support of the Russian Fund of Fundamental Research (projects 03-05-64044a and 04-05-79051k).

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Table 1

Average monthly meanings of elements of a climate on the data GMS "Severo-Kurilsk"

month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	∑
Atm. precipitation, mm	154.4	114.3	133.3	133.7	135.0	92.6	131.8	143.7	162.9	275.1	233.4	170.1	1795
Air temperature , °C	-4.4	-4.5	-2.7	-0.4	2.6	6.7	9.9	11.6	10.2	6.3	1.1	-2.4	2.8
Wind speed, m/sec	4.9	5.2	5.6	4.5	3.4	2.7	2.1	2.4	3.1	4.0	4.6	4.6	3.9
Saturation deficit	1.09	0.99	1.12	1.19	1.30	1.60	1.40	1.90	2.50	2.21	1.81	1.38	

Table 2

Results water-balance of accounts on sites of area

River basin	Drainage area, km^2	Atm. precipitation, mm	Discharge m^3/sek	Modulus of flow, l*s/km^2	Layer of flow, mm	Seepage, mm
East region						
Ytesnaya	7.66	2314	0.481	62.79	1978	-45
Ptichya	12.88	3319	1.554	120.65	3801	-862
Nasedkina	13.29	3397	1.517	114.15	3596	-580
Matrosskaya	11.71	3498	1.224	104.53	3293	-176
Snezhnaya	3.66	3040	0.342	93.44	2943	-284
Kuzminka	5.99	3950	0.679	113.36	3571	-2
Alperina	4.02	2003	0.211	52.49	1653	-31
Gorodskaya	6.7	3142	0.753	112.39	3540	-779
North region						
Savushkina	23.85	2490	1.332	55.85	1759	350
Bratec	13.84	2537	0.778	56.21	1771	385
Zelenaya	23.31	3156	1.652	70.87	2232	543
West region						
Yuryeva	9.22	3283	0.856	92.84	2925	-23
Gorshkova	17.03	3294	1.6	93.95	2959	-46
Lozhkina	12.23	3411	0.963	78.74	2480	550
Pereturpit	10.12	3315	0.775	76.58	2412	522
Lozovaya	11.28	2815	0.738	65.43	2061	373
Burnaya	28.12	3386	2.191	77.92	2454	551

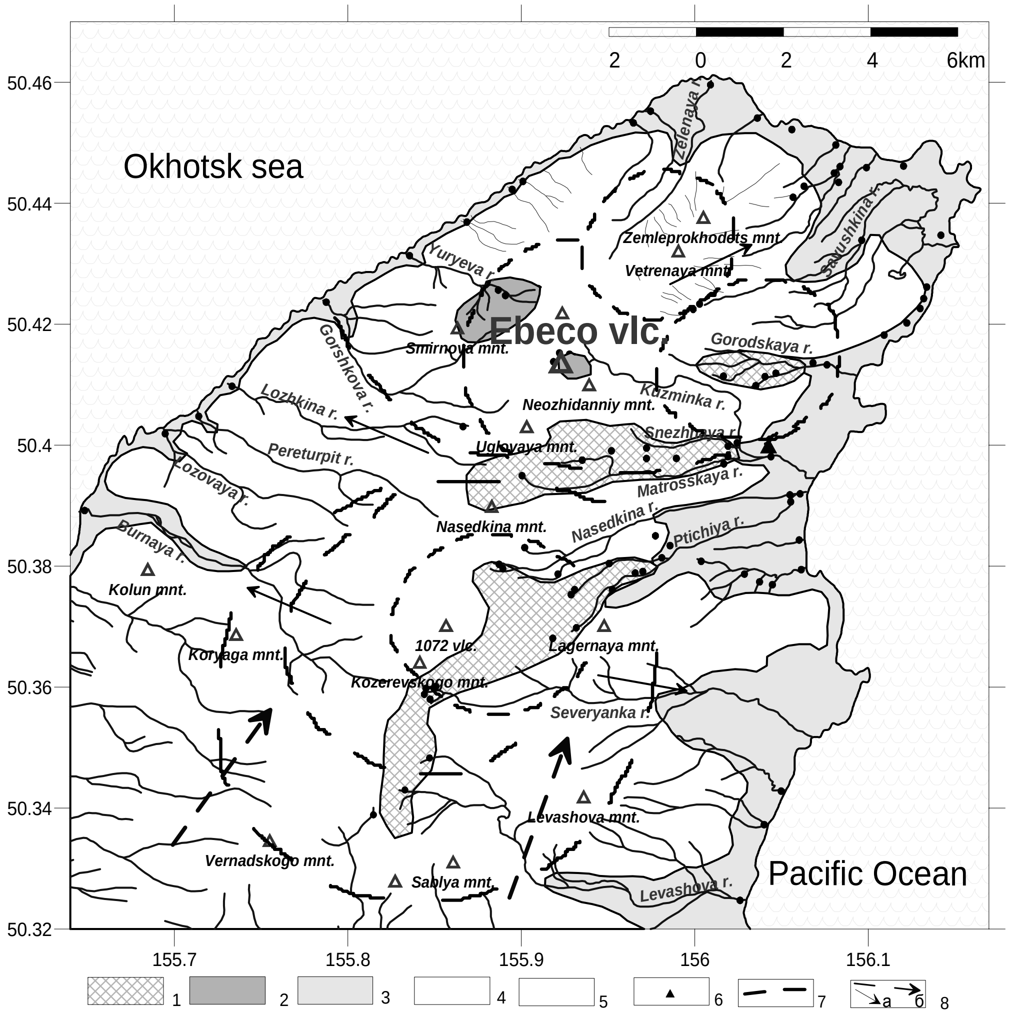

Figure 2: The structural-hydrodynamic scheme of northern part of Paramushir Island. 1 – Areas of unloading of acidic underground waters; 2 – same, ultra acidic waters; 3 – same, groundwaters; 4 – point of sample drawing; 5 – area of power supply and transit of underground waters; 6 – geothermal wells; 7 – main morphotectonic structures; 8 – direction of driving of underground waters.

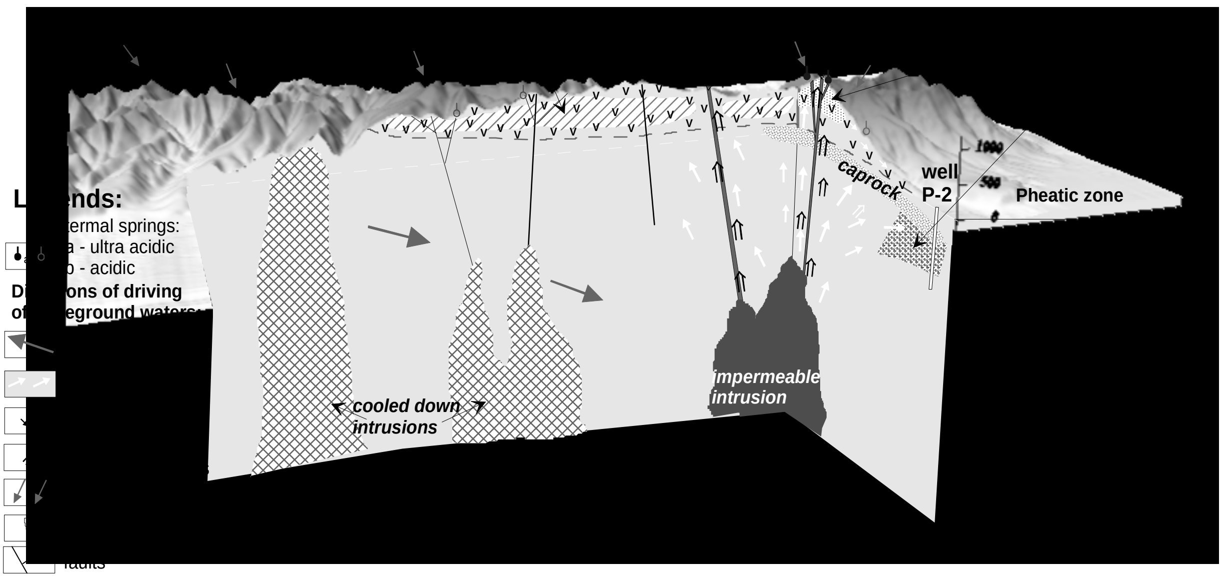

Figure 3: Conceptual structural-hydrodynamic model of the North-Paramushir hydrothermal-magmatic system.