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GEOPHYSICS

Structure Peculiarities of Convective Channels from Thermal Sources in Mutnovskii Volcano (South Kamchatka)

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Peculiarities of the composition of thermal sources in active volcanic regions reflect a multitude of factors influencing the spectrum and content of chemical elements in the solutions reaching the surface. The primary factor is the ratio of deep fluids and meteoric waters. It determines the physico-chemical conditions of precipitation from solutions. This ratio can shift to either side depending on the structural peculiarities of transport: fissured columns and, particularly, open channels favor unconstrained ascent of fluids to the surface. The composition of parent fissures through which filtration of solutions and leaching of elements occur plays an important role. Mixed solutions with a greater proportion of deep components are aggressive and can extract a much greater amount of chemical elements from the volcanic construction rocks than a solution in which the meteoric component has the determining part [1]. The data that appeared in the last decade about the wide range of microelements and their specific associations in thermal waters [2, 3] allow us to describe quantitatively the sources of matter and chemical element precipitation at the surface.

Hydrogeochemical investigations in the Donnoye field of Mutnovskii Volcano revealed thermal sources (mud chambers) with a unique composition of solutions [4]. Their unique property is in the high content of chemical elements including rare-earth elements and platinoids, which differs from the previously known elements in similar volcanic regions of the world by one–two orders of magnitude (Table 1). The data evidence the great role of magmatic fluid in their composition and the existence of open channels or highly fissured structures that transport the solutions to the surface.

A numerical model of fluid migration from a magmatic chamber to the surface was suggested in [4]. The model demonstrates that formation of brines corresponding to the composition of the chambers is possible at the boundary of the secondary boiling, where mixed highly oxidized acid solutions divide into condensate and separant. Ascent of the separant to the surface through open fissures could explain the appearance of the chambers discussed here. Determination of the geometry of structural pathways for reloading the

Table 1. Maximum content of chemical elements in boiling chambers and porous solutions (PS) in Donnoye field of Mutnovskii Volcano, mg/l

Element	Chambers	PS	Element	Chambers	PS
Fe	4.3	53	Cr	60	18
Mn	8.1	400	Co	0.48	5.2
Al	3.0	15	Ni	33	7.1
Li	0.37	14	Cu	0.62	120
Rb	0.52	0.57	Zn	1.9	110
Sr	20	7.2	As	0.61	82
Ba	1.9	0.47	Sb	0.65	0.25
Nb	1.5	17	Tl	0.36	0.35
Zr	0.23	31	Ga	0.94	3.55
Ti	15	360	B	160	450
V	13	430	Be	0.014	0.99

Note: Fe, Al, in g/l.

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chambers was a key problem. The solution of this problem should unite the calculated physico-chemical model and actual data. Electric prospering measurements using shallow range instruments of induction frequency sounding were carried out to test this hypothesis. The physical prerequisite for the application of the electromagnetic sounding (EMS) complex in this case is the high mineralization of solutions in the thermal sources of Mutnovskii Volcano. Thus, the problem of identification of thermal water channels in the mountainous rocks is reduced to the detection of the electrolyte in the parent medium with relatively low specific electric resistivity [5, 6]. The objective of our work was to investigate the distribution structure of volume electric conductivity to a depth of 6 m, which allowed us to reveal the configuration of supplying channels to the chambers and distribution of porous waters in the subsurface space of the Donnoye field.

THE OBJECT OF RESEARCH

Mutnovskii Volcano is located 75 km south of Petropavlovsk-Kamchatskii. Its body, with a maximal height of 2323 m above sea level, consists of four tightly compressed sequentially formed stratocones with summit calderas and daughter intracaldera structures, while the entire massif is formed of numerous cones of secondary eruptions [7]. Earlier, eruptions occurred with the transport of juvenile basalt material along with phreatic eruptions. Beginning from 1904, the material of the latest eruptions was resurgent, which was established for eruptions in 1927–1929, 1960–1961, 2000, and 2007 [8–10]. Over a long time interval, from 1961 to 2000 and during calm periods between the activation phases in the beginning of the 2000s, Mutnovskii Volcano was in the stage of fumarole-hydrothermal activity with unusually high energetic parameters 1800–1900 MW, which is considered by a number of scholars as passive eruption [10, 11].

The Donnoe field of the volcano (northeastern crater) is the bottom of a lake, which existed up to the 1950s. Later, it disappeared and a fumarole field with varying shape appeared in its place. Three sulfur fumaroles, a large mud chamber, and a multitude of small thermal sources are active in the field more or less continually. The temperature, color, and their consistency (water–rock) vary in a wide range: from small transparent outcrops of boiling water to black chambers (the proportion of suspended matter in them is as high as 10%). Sometimes chambers appear with a yellowish, whitish, or greenish color of the boiling mixture there. A snowfield is located on the slope of the field, which supplies water into the brook during the melting period. The brook flows in the field, and part of its water mixes with the solutions in the chambers.

METHODS

In 2007, geophysical investigations were carried out using the method of electromagnetic inductive sounding with instrumental programming complex EMS. The complex was developed at the Institute of Oil and Gas Geology and Geophysics, Siberian Branch, Russian Academy of Sciences (IOGGG SB RAS).

The study region in the Donnoye field was divided into measurement points over a grid 1 × 1 m (Fig. 1). The soundings were performed at 14 frequencies in the range 2.5–250 kHz. The obtained information was processed using the Isystem programming code as part of the complex. Geoelectric sections over nine profiles of measurements were plotted. The length of the profiles was 29 m, and the distance between them was 1 m. Each profile reflects the distribution of the apparent specific resistivity of the ground (ρ). The final visualization (quasi-three-dimensional model of subsurface distribution of specific electric conductivity) was performed using an original programming code developed at IOGGG SB RAS. The EMS as the instrumental realization of the method of frequency sounding (FS) is most applicable in this case owing to its compact size, low weight, and high performance of field research with the possibility of immediate visualization of results.

After the geophysical investigations (charts and distributions were obtained), we performed geochemical testing of solutions in Donnoye field. We tested boiling chambers. The samples from boiling chambers were taken using a Teflon sampler. Small pit-holes with a depth of 50–70 cm were made in the thermal area, from which the moist substance was taken to extract porous solutions. The pit-holes were located next to sample substances with different ρ. The samples were packed in hermetic plastic packages for transportation.

Porous solutions were extracted from moist samples under a pressure of 100 at in laboratory conditions. The cation composition and concentration of microelements in all solutions were determined using the method of Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) on the IRIS Advantage instrument at the Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences. The contents of Cl and SO_4 were measured using the method of high efficient fluid chromatography with indirect UV-detection of anions in a column with inverse phase modified octadecyltrimethylammonium bromide on a microcolumn chromatograph Millichrom A-02 manufactured by EcoNova (Russia).

RESULTS

According to the results, the specific resistivity of ground in the study region ranges within 0.1–27 Ohm m. It is likely that low resistivity is related to the saturation of the ground with highly mineralized thermal waters, while high resistivity is characteristic of ground washed

Fig. 1. Thermal area of Donnoye field with marked lines of profiles.

by thawed water of the snowfield. Judging from the distribution of ρ, all sections are characterized by high resistivity in the left part and low resistivity in the right part (Fig. 2). The spatial distribution of conducting zones points to the existence of subsurface vertical channels strongly saturated with highly mineralized thermal waters and mud chambers confined to the surface manifestations of these waters. Vertical channels are separated from each other with walls of increased resistivity 1–3 m thick. It is our opinion that the walls can be formed of denser less permeable rocks for the solutions. Interpretation of the results is confirmed when geoelectric sections are considered one after another with increasing distance from the line of chambers. The closest profile to the line of chambers shows that mineralized hydrothermalites reach the surface from a source, the location of which was not found at the given depth of sounding. However, the structure of supplying channels (we assume that the sounding depth was approximately 6 m) denotes their stable configuration.

The composition of solutions outcropping to the surface varies in wide limits (Table 2), which can be explained from the analysis of zonality of subsurface space. The zone with low ρ corresponds to chambers SDP 2, 3, and 5. Chamber SDP 4 is formed from a local zone with higher values of ρ. Three chemical elements are reference ones for fluctuations of the ratio of thaw water to hydrothermal solutions. They are the chloride-ion, aluminum, and titanium. The chloride-ion is the determining component in total mineralization of solutions. Comparison of the pattern of the distribution of ρ in the vertical section of profile 9 with the composition of the mud chambers explains the variations found even in closely located mud chambers. They are determined by fine hydrogeochemical zonality of subsurface space, which was revealed during electromagnetic sounding. For example, in pit-hole no. 2, porous solutions obtained from three vertical levels reflect increasing mineralization according to the distribution of ρ on the basis of the concentration of many chemical elements (Fig. 2, Table 3).

Regions of high conductivity interpreted as transport channels of highly mineralized separant become thinner as the distance from the chamber increases. They become less pronounced, and their upper parts are covered with rocks of lower conductivity (i.e., thermal waters do not reach the surface). The correlation between the total mineralization of porous waters, the contents of Cl and Al, and the electric conductivity of solutions was clearly pronounced in porous solutions along profile 4 (Fig. 3), which was reflected in the complex zonality of this site. The mechanism of zonality formation can be explained by the peculiarities of mixing between water from thawed snow flowing from the snowfield (the left part of the sections corresponds to this site) and thermal solutions. This zonality can change depending on the time of year and water saturation of the ground. Porous solutions of the thermal area obtained in 2006 (Table 1) differed strongly from the porous solutions from the substance taken at practically the same place in 2007. It is likely that this is related to the fact that during the period of dry weather, the most mineralized solutions (Fig. 2, inset B in profile 9) were

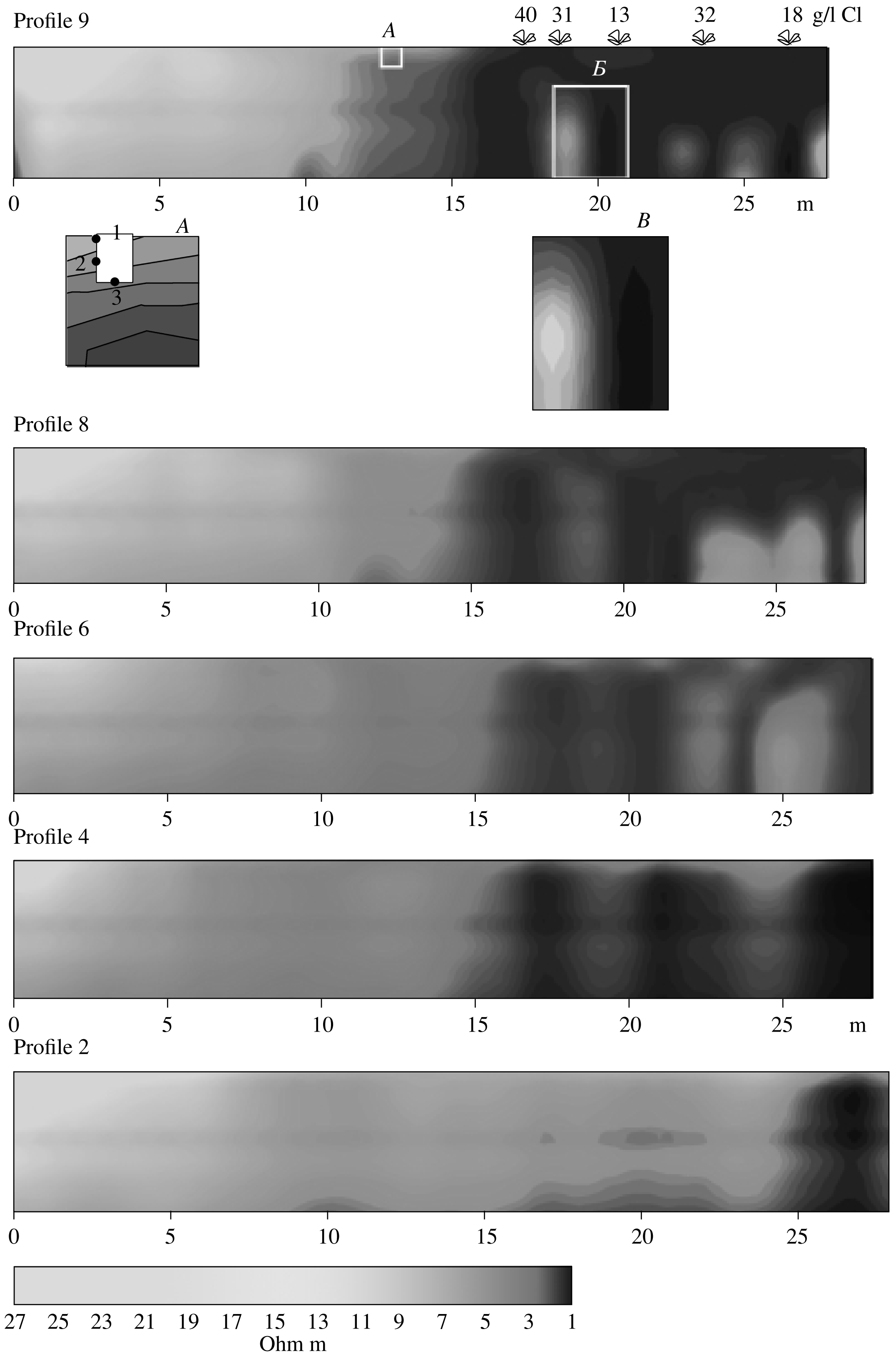

Fig. 2. Parallel geoelectric sections of the thermal area in Donnoye field. In the upper right corner, mud chambers and content of chlorides in the chamber solutions (Table 2); (A) Schematic of testing pit-hole (depth 50 cm); (B) Fragment of hydrogeochemical zonality of subsurface space.

Table 2. Compositions and indicators of solutions in mud chambers in Donnoye field of Mutnovskii Volcano

Element	SDP 2	SDP 3	SDP 4	SDP 5	SDP 7	SDP 9a
pH	−0.26	−0.31	0.18	−0.03	0.33	0.29
Eh, mV	609	590	510	530	550	640
Cl^-	39000	31200	13100	31600	18400	2700
SO_4^{2-}	4400	3300	2700	8500	2660	630
PO_4^{2-}	32	40	15	120	45	19
Na	160	150	67	500	160	97
K	210	200	120	740	41	120
Ca	200	150	53	170	700	70
Mg	80	53	17	46	160	24
Fe_{total}	320	170	64	190	390	64
Al	1100	1860	1100	2700	2300	880
Mn	5.6	2.8	1.1	3.0	5.3	1.1
Ti	9.7	7.9	0.78	3.2	1.2	0.74
V	2.4	2.3	0.92	4.5	5.4	0.99
Co	0.2	0.03	0.02	0.05	0.05	0.010
Cr	22	0.38	2.3	5.0	4.4	0.25
Ni	12	0.12	0.93	1.8	1.6	0.06
B	110	33	9.1	32	30	8.2

Table 3. Vertical variations in the content of chemical elements and indicators in porous solutions (pit-hole 2), mg/l

Indicator	Pit-hole 2-1	Pit-hole 2-2	Pit-hole 2-3
pH	2.97	2.32	1.34
Eh	577	585	630
δ, mS/cm	45.2	46.6	88
Cl^-	6.9	7.3	25
SO_4^-	5.0	5.8	3.5
F^-	0.68	0.81	1.6
Ca	1600	1280	1150
Mg	120	150	310
K	15	36	51
Na	83	150	210
Al	1160	1130	1650
B	3.1	3.4	27
Co	0.1	0.11	0.48
Cu	0.03	0.08	3.8
Fe	230	370	1000
Mn	4	5.8	8.4
Ni	0.33	0.4	0.58
Sr	2.4	4.4	8
V	4.9	5.4	7.3
Zn	2.9	3.1	4.2

Note: Cl^-, SO_4^- in g/l.

located near the surface: they correspond to zones of black color. We think that their composition is closest to the separant that separates at the phase barrier and can reach the space near the surface. This made it possible to find solutions with extreme concentrations of chemical elements [12], and the results allowed us to explain their origin.

Thus, we tested and developed methods of remote sounding of a volcanic structure with contrasting parameters of specific electric resistivity to a depth of six meters. We obtained geoelectric charts and sections reflecting the spatial distribution of specific electric resistivity in the medium.

The configuration of supplying channels for thermal sources was determined in the subsurface space of Donnoye fumarole field, which is pronounced in the vertical zones of low resistivity that confirmed the hypothesis about the transport of brines from anomalous sources through the open fissures zones.

Hydrogeochemical zonality of porous waters in the thermal area was found, which is caused by the mixing of inflowing brines and meteor waters in different proportions. This is the cause of the appearance of thermal sources (mud chambers) with different compositions, colors, and physicochemical parameters from one site. The zones of low resistivity have complex spatial geometry, which is manifested in the zonal distribution of solutions with different mineralization under the surface of Donnoye field.

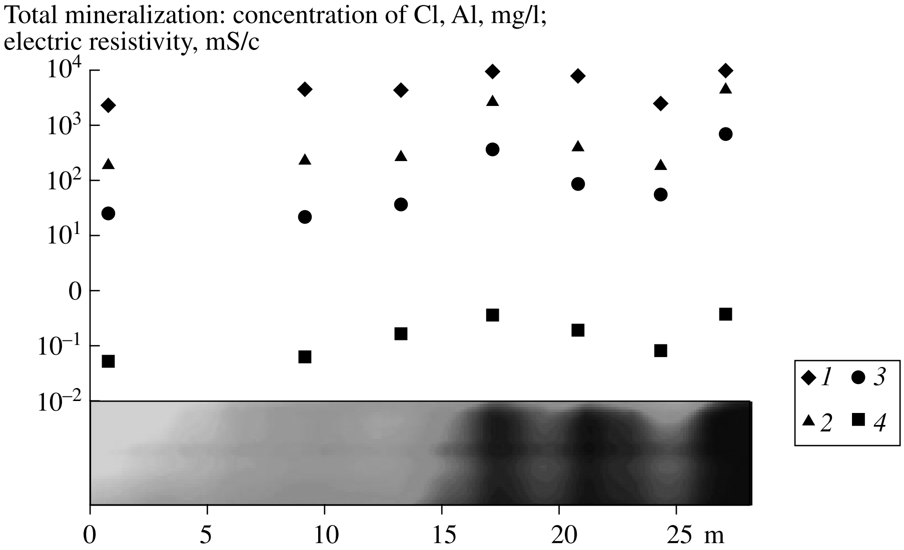

Fig. 3. Distribution of apparent resistivity of the medium (ρ) (see Fig. 2) versus parameters of porous solutions: (*1*) total mineralization; (*2*) chloride content; (*3*) aluminum content; (*4*) electric resistivity.

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