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Geofluids of Avachinsky-Koryaksky Volcanogenic Basin, Kamchatka, Russia

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ABSTRACT

Avachinsky-Koryaksky volcanogenic basin with area of 2530 km^2 is located in Petropavlovsk-Kamchatsky city and includes five quaternary volcanoes (two of which, Avachinsky (2750 m.a.s.l.) and Koryaksky 3456 (m.a.s.l.) are active), sub-basins of volcanogenic and sedimentary Neogen-Quaternary deposits, located in a depression formed at the top of Cretaceous basement rocks. Magma fluids emplacement zones are clearly detected by local earthquakes distributions below Koryaksky and Avachinsky volcanoes at depth elevations between -5.5 and +2.0 km and between -1.5 and +2.0 km, respectively. The water isotope (δD, δ18O) data shows that those volcanoes are also acts as recharge areas adjacent to the thermal mineral springs (Koryaksky Narzans, Isotovsky and Pinachevsky) and wells of the Bystrinsky aquifer. δ13C in CO^2 from CO^2 springs in NW foothills of Koryaksky volcano are formed as a result of mixing of magmatic gases and melting glaciers waters. High sensitivity of thermal springs to regional and local seismic activity events pointed to hydraulic connection between magma emplacement zone beneath Korykasky volcano, adjacent hydrothermal systems and methane reservoirs. Hydrodynamic TOUGH2-EOS9 model of Avachinsky-Koryaksky volcanogenic basin was developed and calibrated, based on water level data in 13 deep wells. Inverse modeling yielded estimation of the total rate of meteoric recharge 6 m^3/s and the maximum groundwater head below volcanoes +900 m.a.s.l. It is suggested that shallow methane CH_4 reservoirs penetrated by wells in Neogene - Quaternary layer around Koryaksky and Avachinsky volcanoes, and Pinachevsky extrusions may be formed as a result of heating from the magma emplacement reservoirs beneath volcanoes to the hosted gas hydrates and organic sediments. The area of potential methane accumulation is accounted ~650 km^2.

1. INTRODUCTION

Avachinsky and Koryaksky volcanoes are located 25-30 km from the city of Petropavlovsk-Kamchatsky, whose population is about 250 thousand people, holding in their interior significant resources of underground heat and groundwater, and presenting a potential danger as well. The cone of Avachinsky volcano originated 3500 years ago and had 15 eruptions in historical time (since 1737). Koryaksky volcano showed significant increase in fumarole activity in 2008-2009. Magma intrusion into aquifers can lead to increased volcanic activity and hydrothermal explosions. Creating thermohydrodynamic models of Avachinsky-Koryaksky volcanogenic basin is needed to solve the following problems: 1 - to determine the flow rate of infiltration recharge and calculation of groundwater level surface in the area of volcanoes; 2 – to determine temperature and permeability distribution in the area of volcanoes; 3 – to assess the conditions of formation and operating reserves of thermomineral and freshwater deposits as well as gas deposits within the basin; 4 – to analyze a variety of thermohydrodynamic and hydrochemical regime of groundwater springs associated with seismic events.

2. AVACHINSKY-KORYAKSKY BASIN HYDROGEOLOGICAL STRATIFICATION AND FLUIDS RECHARGE/DISCHARGE CONDITIONS

2.1 Hydrogeological Stratification

Avachinsky-Koryaksky volcanogenic basin with area of 2530 km^2 is located in Petropavlovsk-Kamchatsky city and includes five quaternary volcanoes (two of which, Avachinsky (2750 m.a.s.l.) and Koryaksky 3456 (m.a.s.l.) are active), sub-basins of volcanogenic and sedimentary Neogen-Quaternary deposits up to 1.4 km thick. The basin is located in a depression formed on a top of Cretaceous basement rocks and generally characterized by low temperature gradient of 24 °C /km (Figs. 1-3).

The basin basement is composed of Upper Cretaceous K_2, which is represented by metamorphic rocks: metasandstone, metasiltstone, phyllites with interbedded shales and microquartzites. Porosity values are tenths of a percent. The rocks are virtually impermeable with 0.001-0.01 mD. However, there are fracture zones produced at testing the flows of reservoir water with flow rates from 4.6 to 530 m3/day, in the depth interval of 1438-1490 m (well E1). The average thermal conductivity of Cretaceous deposits is 2.8 W/m °C.

Neogene-lower Quaternary aquifer complex is composed of pyroclastic and volcanogenic-sedimentary formations. The values of porosity are quite high: 0.36-0.48. The specific well productivities are from 0.0004 kg/s • m (well P2) to 0.01 kg/s • m (well ГК-1 Pinachevskaya). The average thermal conductivity of Paleogene-Quaternary deposits is 1.5 W/m°C. The aquifer system of Pinachevsky extrusions Q_{1-2} is composed of andesites and rhyolites extrusions and includes vent andesite, dacite and rhyolite formations (with a thickness of more than 200-500 m). According to laboratory studies, the porosity is 0.12, and the permeability is 24 mD.

The artesian volcanogenic basin (AVB) includes the aquifers of water-glacial formations comprising Holocene alluvial deposits, upper Pleistocene-Holocene marine and alluvial-marine horizons, upper Pleistocene glacial and glacioaqueous complex, and

Holocene aquiferous proluvial and diluvial-proluvial complex. As results of well testing of Bystrinskoye aquifer, the permeability ranges from 10 to 3000 mD.

Koryaksky and Avachinskiy volcanoes (Q_{3-4}) are composed of basaltic andesites and basalts form a groundwater recharge area of the volcanogenic basin.

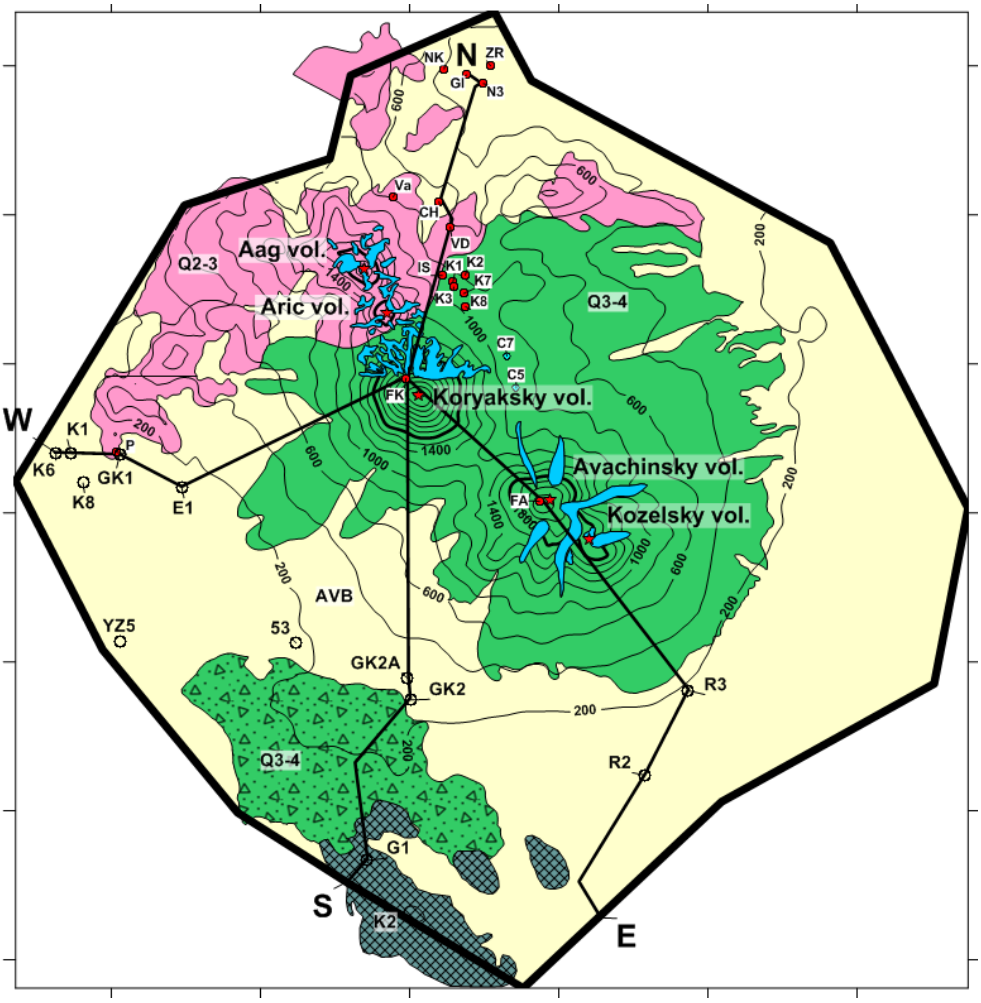

Figure 1: Geological map of Koryaksky-Avachinsky volcanogenic basin. Geological units: K2 – Cretaceous basement rocks, N-Q1 - volcanogenic and sedimentary Neogen-Quaternary deposits, Q2-3 – Pinachevsky extrusions sub-basin, AVB – artesian-volcanogenic basin, Q3-4 – Avachisky, Koryaksky, Kozelsky volcanoes and their erupted products nearly of Petropavlovsk-Kamchatsky. Thermal mineral springs: K1,K2,K3,K7,K8 –Koryaksky Narzans, IS – Isotovsky, VD – Vodopadny, CN, CH- Chistinsky, Va – Vakinsky, N3 – Nalychevsky Pool #3, GI- Grifon Ivanova, NK – Nalychevsky Kotel, ZR – Zheltorechensky, P1,P2 – Pinachevsky. Cold springs: C5 and C7. Axis scale is10 km.

2.2 Volcanic/Magma recharge/discharge

The average discharge rates of Koryaksky and Avachinsky active volcanoes during their existence are estimated at 80 and 150 kg/s, respectively. The activation of Koryaksky volcano fumarole activity began on November 23, 2008 in the form of enhancing steam and gas activity in the fracture on the northwestern flank of the volcano at spout thermal power of ~ 40 MW and gas-steam fluid discharge of ~ 15 kg/c. By the end of December, thermal power and steam discharge increased to ~ 400 MW and ~ 150 kg/c, in the plume of the upper (main) vent appeared ash admixture. The superior vent, near the mouth of the crater, was basic and characterized by an order higher steam discharge than the lower. In January 2009, steam discharge out of these vents amounted to ~ 170 kg/s and ~ 20 kg/c, respectively. Since late April, steam-gas activation continued only from the main vent (at the beginning of June 2009). The average thermal power and steam discharge for Avachinsky volcano from late 2008 to early 2009 was estimated at 10-15 MW (4-5 kg/s). The thermal power of steam and gas plumes of volcanoes was estimated by using S.A.Fedotov’s formulas (Ivanov, 2009).

According to the seismic data (2009, KB GS RAS), earthquakes coordinates were confined to two reservoirs: reservoir "A", centered in the cone of Avachinskiy volcano at depths between -1500 and + 2750 m.a.s.l., having a diameter of about 2 km; and reservoir "K" in the structure of Koryaksky volcano at the depth range between -6500 and 2000 m.a.s.l., characterized by horizontal dimensions of 15 x 3 km and extending into the submeridional direction (Figs. 2, 3 and 7). These reservoirs were apparently characterized by higher permeability and temperature, as they trace hydraulic fracturing zones at magma intrusion, supplying Koryksky and Avachinsky volcanoes.

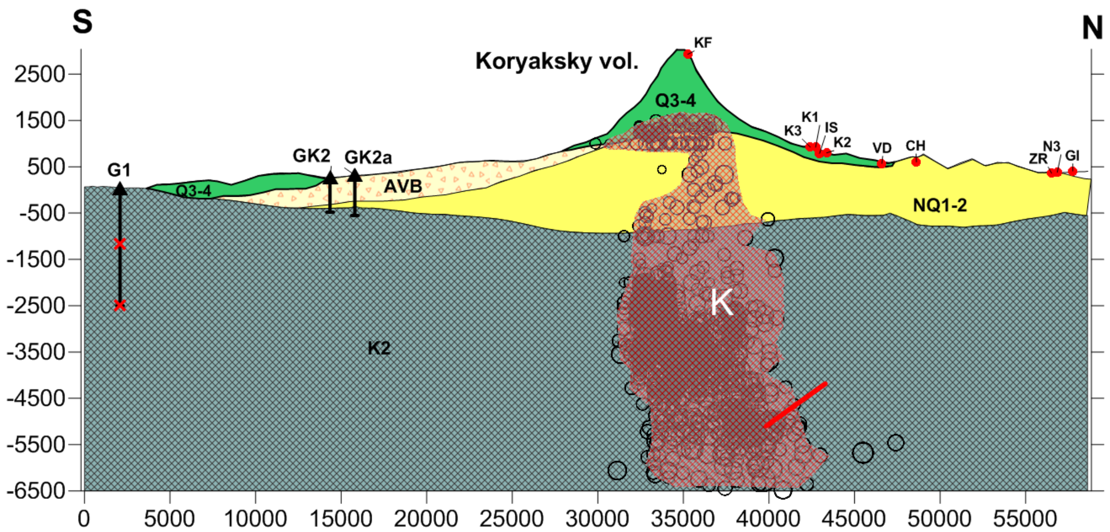

Figure 2: Geological cross-section NS of Avachinsky-Koryaksky volcanogenic basin (see map on Fig.1). Wells, hot springs and "K" reservoir configuration (cross hatch) are shown and defined on the basis of seismic records. Circles plots hypocenters of local earthquakes (2009, Kamchatka Branch (KB) Geophysical Service of Russian Academy of Science), and red thick line expresses trace of the fracture induced MEQs 2.08.2011.

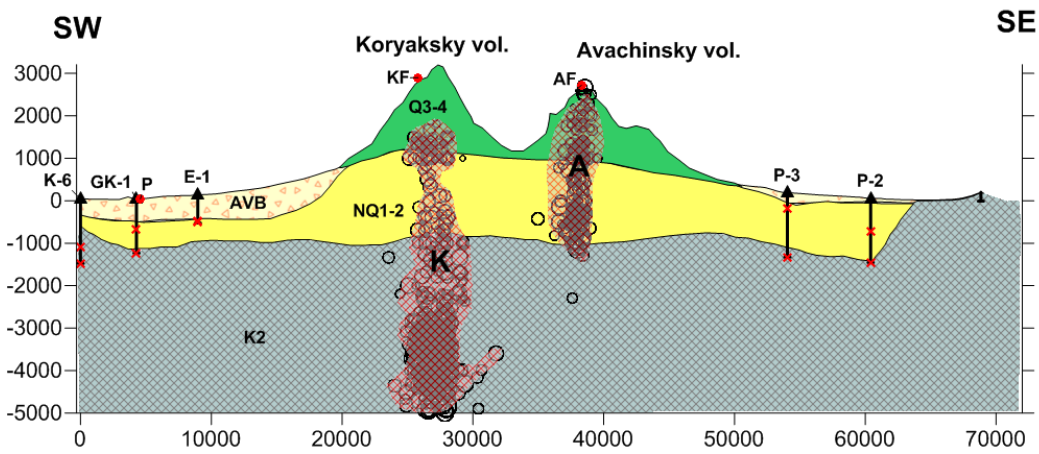

Figure 3: Geological cross-section WS of Avachinsky-Koryaksky volcanogenic basin (see map on Fig.1). The figure shows wells, hot springs and configurations of reservoirs "K" and "A" (cross hatch), defined on the basis of seismic records. Circles are hypocenters of local earthquakes (2009, KB Geophysical Service of Russian Academy of Science).

2.3 Water recharge/discharge conditions

Intervals of deep wells sampling (Table 1), encountering Koryaksky-Avachinsky basin basement (K_2, ₽$_3$-N_1 as), were characterized by the chemical composition, corresponding to the dilution of oceanic sediment water due to the infiltration of meteoric waters. Hence this was a dominant Cl-Na waters with minor concentrations of HCO_3, Ca and Mg, while SO_4 in trace concentration in the most of cases. There was no indication of significant water metamorphization. The Cl/Na ratios were close to seawater values. Some increase in Ca and Mg may be related to CO_2-leaching processes from the host rocks.

By gas composition, the fluids of volcanic basement rocks (outside reservoir "K") were characterized by the broad distribution of methane (~70 об.% at wells R3, K1, GK1, Table 2). The most striking example was the well P3, having revealed a gas deposit at the depth interval between 366 and 455 m at a pressure 24.2 of bar. The result of this well in the full range of 366-1503 m showed the production rates were 3.15 kg/s of water and 4.02 l/s of gas, respectively, at a discharge temperature of 18°C.

The thermal mineral water discharged by springs on foothills of the volcanoes significantly differed from the water circulated in the basement rocks. Spring water was characterized by a presence of CO_2 in gas phase (Table 2), lower pH values (Table 1) and lower salinity (1 - 4 g/l), which was related to significant mixing of those waters with meteoric waters in near surface conditions. This was HCO_3-Na water with small Cl concentrations, comparable with Cl concentrations of adjacent rivers and creeks.

Increase in SO_4 concentration was also observed, especially in Isotovsky spring (IS). All features mentioned above may be explained as a result of interaction of meteoric water enriched by volcanic CO_2 gas upflows with volcanogenic rocks. CO_2 leaching yields Na- and sometimes Ca- enrichment. Sources of SO_4 may include either volcanic gases (with CO_2), or leaching by meteoric waters from hydrothermally alternated rocks in sub-crater zones of volcanoes. Formation of such waters in kinetically active zones was reflected by large variance of geothermometer values of 200-300 °C (Table 1), while the basement water showed more narrow range of the geothermometer values.

The conditions of water recharge of AVB and thermal mineral springs were quite well identified on the basis of the data on the isotopic composition of groundwater (Fig. 4). Area of water recharge for Koryaksky Narzans, Izotovsky springs, and Pinachevsky spring (№ 2), and wells of Bystrinsky groundwater deposit were located at elevations of 2000 - 2500 masl. By hypsometric position, these can only be slopes of Koryaksky and Avachinsky volcanoes, especially glacier sites. Area of water recharge for the group of Chistinsky Narzans was located at elevations of 800-1500 m abs, which corresponded to the position of the central part of Pinachevsky extrusive mass with volcanoes Arik and Aag. By chemical and gas composition, fluids of thermal mineral springs in the zone of reservoir "K" differed sharply from the basement groundwater with predominance of CO_2 in the gas composition of 78-97.5 % with high temperature Na-K geothermometer values of more than 290-320 °C (Table 1).

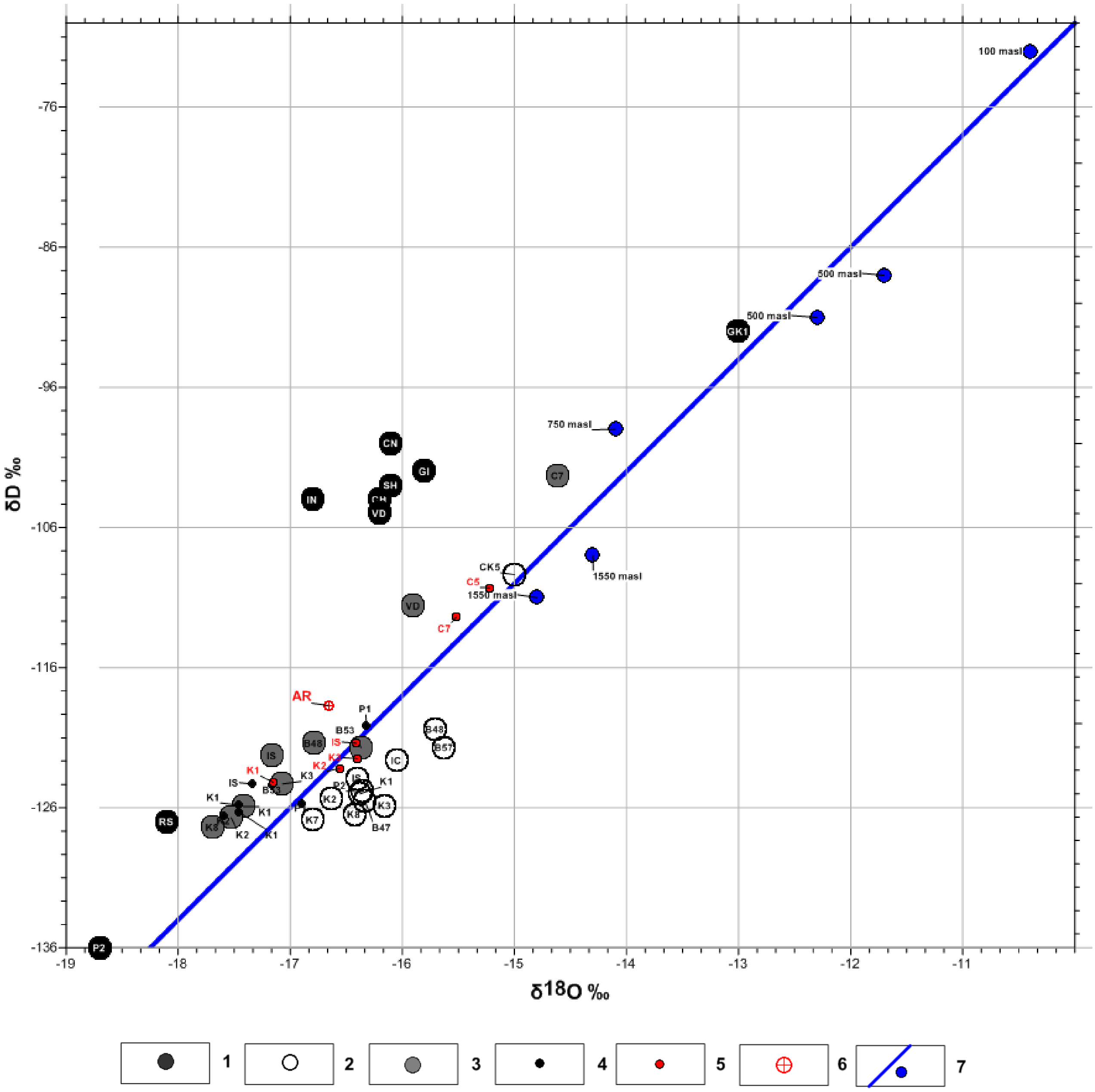

Figure 4: Isotope composition of water (δD and δ^{18}O). Legend: year of sampling: 1- 2009, 2- 2010, 3- 2011, 4- 2012, 5- 2013, 6 – 2013; 7 for meteoric water samples (with elevations, m.a.s.l.) and meteoric line. They were sampled by Kiryukhin and analyzed by Polyakov (2009) and Dubinina (2010). Sample analysis of 2011, 2012, 2013 and 2014 data were performed by Voronin and Polyakov using LGR IWA 45EP isotope analyser. Thermal mineral springs: K1,K2,K3,K7,K8 –Koryaksky Narzans, IS – Isotovsky, VD – Vodopadny, CN, CH- Chistinsky, Va – Vakinsky, N3 – Nalychevsky Pool #3, GI- Grifon Ivanova, NK – Nalychevsky Kotel, ZR – Zheltorechensky, P1,P2 – Pinachevsky. Cold springs: C5 and C7. Rivers: AR-Avacha river (Elisovo), RS- Right Shumnaya river. Wells: GK1 – Pinachevsky area, B47,B57, B48, B53 – Bystrinsky cold aquifer (around well 53). See map on Fig.1 with positions of sampling points. Springs names are given according to M. Petrov.

The isotopic compositions of $\delta^{13}C$ carbon in CO_2 in the samples of free gas, carbonated springs at the north slope of Koryaksky volcano (K2, K3 and IS) (Table 2) were in the range of 9.0 - 6.9 ‰, that were within the range of Koryaksky and Avachinsky fumaroles (see below). They pointed out to significant magmatic fraction in CO_2 component of the springs mentioned above.

Table 1: Water chemical composition of hot springs, cold springs and flowing wells of Koryaksky-Avachinsky volcanogenic basin, according to sampling data 1970-2011. Wells: GK1, G1, K6, K8, R3, R2, 53, E1; hot springs: IS, K1, K2, VD; cold springs: C5 (see map on Fig. 1 with positions of sampling points). GK1, G1 – data from Ryabinin (pers. com., 2011), K6, K8 (Serezhnikov et al, 2000), R2, R3 (Evtukhov et al, 1995), E1 – Kopylova (pers. com., 2011). The rest of the samples were collected by Kiryukhin and analyzed in Center for Chemistry of Far East Branch of Russian Academy of Science. T_SiO$_2$ и T_Na-K – hydrochemical geothermometers (T_SiO$_2$= 1309/(5.19-LOG10(I3))-273 - Fournier, 1977, and T_Na-K=855.6/(LOG10(Na/K)+0.8573)-273 - White, 1970).

##	Data	pH	Cl-	HCO_3^-	SO_4^{--}	Na^+	K^+	Ca^{2+}	Mg^{2+}	SiO_2	T_{Na-K}	T_{SiO2}
						wells						
GK1	04.10.1970	7.5	2199	207		1050	70	241			148	
G1	14.04.1988	8.8	4929	502	100	3450	48	24	24		42	
K6	17.11.1990	8.5	2124			1175	25	119	24	46	64	98
K8	17.11.1990	8.3	6358	14	13	3125	91	598	234	44	85	96
R3	05.06.1992	7.6	12869	144	16	6667	167	679	271	61	75	111
R2	15.03.1993	8.2	6901	518		4308	0	110	122	11		43
E1	30.08.2011	12.1	344	68	10	285	47	36	2	2		
53	05.07.2011	8.2	24	51	154	28	3	28	22	35	182	86
						springs						
P2	30.05.2010	7.4	353	231	5	240	9	23	28	53	99	105
IS	28.07.2011	6.9	28	800	1114	323	103	401	2	66	358	116
K1	29.07.2011	6.6	32	678	115	64	14	76	92	40	292	92
K2	29.07.2011	6.3	41	866	134	80	21	84	120	51	320	103
VD	29.07.2011	6.5	<0.3	429	67	47	22	38	47	111	451	143
C5	30.07.2011	6.5	1	9	1	1	1	1	1	3		

Table 2a: Gas Chemistry and Carbon isotopes data. Chemical and isotope composition of free gases (об. %) of thermomineral springs and flowing wells of Koryaksky-Avachinsky volcanogenic basin, according to sampling data 2010-2013. Sampling performed by Kiryukhin, Rychkova, and Lavrushin. Chemical analyses were performed in Center for Chemistry of Far East Branch of Russian Academy of Science (analysis performed by Guseva). Isotope analysis ($\delta^{13}C$) was performed by Pokrovsky. GK1 by using data from Ryabinin (pers. com., 2011), R3 and data from Evtukhov (1995).

##	Data	H_2	Ar	O_2	H_2S	N_2	CO_2	CH_4	Sum	$\delta^{13}C$ (CH_4)	$\delta^{13}C$ (C_2H_6)	$\delta^{13}C$ (CO_2)
						wells						
K1	07.08.2013	0.005	0.1	0.1	1.57	22.6	0.7	71.31	96.3	-34	-25.6	-27.7
R3	23.10.2013	0.017		0.1		37.5	0.1	60.7	98.3	-61	-	-49.7
R3	05.06.1992					26	0.2	73	99.2			
GK1	25.05.1988	0	0.1	0		20.9	0.2	78.7	100			
						springs						
K2	09.07.2010	0	0.1	0.2		11	88.6	0.04	99.9			
K2	25.09.2010	0.001	0.3	2.9		28.8	68.1	0.03	100			
K2	06.08.2013	0.105	0.2	0.1	<0.0086	23.7	75.6	0.04	99.8			
K2	06.08.2013			0.1		27.1	72.4	0.05	99.6	-40.3	-	-8.8
K3	06.08.2013			0		62.2	37.7	0.05	100	-23.1	-	-9
CH	29.07.2011	0	0	0		2.5	96.7	0.08	99.3			
IS	06.08.2013	<0.005	0	0.3		2.9	95.2	0	98.4	-36.8	-	-6.9

By the isotopic composition of carbon $\delta^{13}C$ in CH_4 in free gas samples, methane wells K1 (Ketkinskoye geothermal field, $\delta^{13}C$=-34‰) and R3 (Radyginskaya area $\delta^{13}C$ = -61 ‰) differed significantly: the gases discharged from well K1 were formed in higher temperature conditions than the gases penetrated by well R3, where significant fraction of methane was “marsh methane” of the microbial origin. Interestingly, data obtained from wells of gas condensate fields in western Kamchatka were within this range (N-Kvakchikskoye- -36.9 - -38‰, Kshukskoye - 43.1 ‰), as a result of induced magma-hydrothermal gas generation in the hosted volcanogenic-sedimentary rocks. Nevertheless, low values of the $\delta^{13}C(CO_2)$ (-49.7 ÷ -16.8 ‰) in methane wells pointed out that some CO_2 here was non-magmatic origin (Table 2), and paragenetically related to methane sources.

Note that chemical and isotopic compositions of the volcanic gases from Avachinsky and Koryaksky volcanoes fumaroles (AF, KF shown in Fig. 1) were described by Taran (1997). According to Taran, those gases are characterized by the range of isotopic composition reflecting mixture of the magmatic and meteoric end members (-58‰ $<\delta D<$-30‰, -0.1‰$<\delta^{18}O<$+7‰, -11.8$<\delta^{13}C<$-

5.2). High methane concentration (up to 0.3-0.6 mmole/mole) suggests considerable amount of regional methane-reach thermal water from the basement of volcanoes.

Table 2b: Gas concentration (ml/l) dissolved in water phase of the Avachinsky-Koryaksky basin wells and springs (P1-Pinachevsky-1).

##	Date	H_2	He	Ar	O_2	N_2	CO_2	CH_4
P1	2010-2014		0.00095	0.4	3.0	19.2	7.6	0.5
Well 53	3.07.2013	0.002		0.4	0.7	22.2	0.2	0.0002
E1	1984	0.2		0.6	10	60	0.3	29

3. SPRINGS AND WELLS SENSITIVITY TO EARTHQUAKES

Continuous observations in Pinachevsky springs began in 1977. Measurements were conducted every 3 days including air pressure, air temperature, flow rates, and temperatures as well as the gas dissolved in the water phase was sampled for chemistry analysis. It was found that strong earthquakes in south-east of Kamchatka induced the following changes in the parameters in Pinachevsky springs: varying flow rate, fluid temperature increase, mineralization increase, and methane concentration increase (Grits, 1983, 1986; Bella, 1998; Biagi, 2003; Kopylova, 2005, 2006; Khatkevich, 2006). Fig. 5a shows examples of recorded post seismic excursions of the parameters mentioned above.

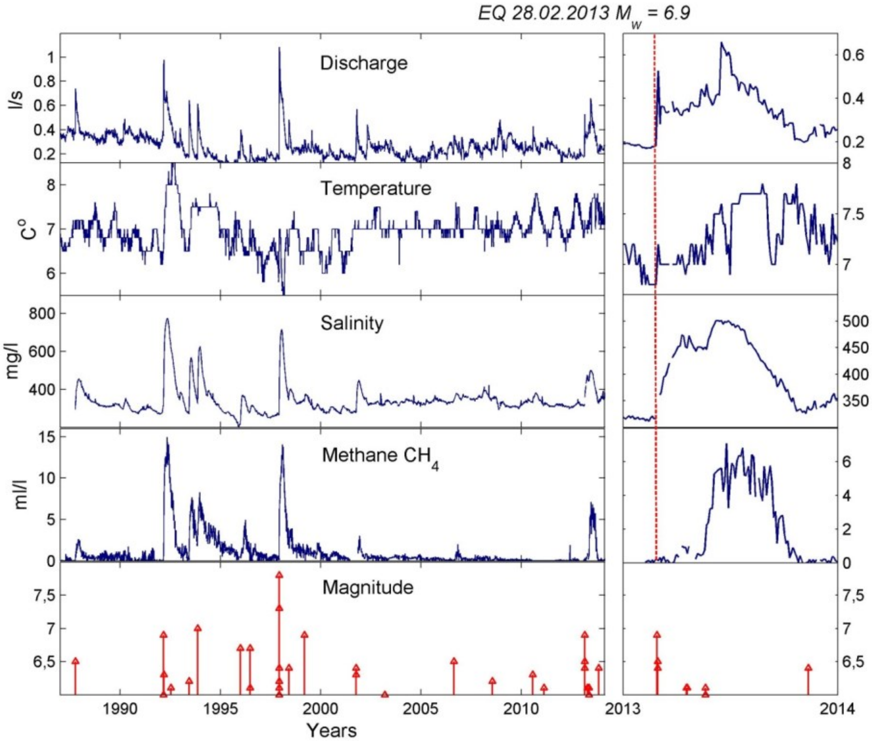

Figure 5a: Post-seismic excursions of the Pinachevsky-1 spring parameters (flow rate discharge, l/s; temperature, °C; total mineralization, mg/l; methane concentration, ml/l) versus of the earthquakes occurrence and magnitude. The earthquakes are referenced to USGS http://earthquake.usgs.gov/earthquakes/search/ with M ≥ 6.0, at depth H ≤ 50 km at a distance less than 400 км from the spring location.

Additionally, since 2010, the temperature of spring Pinachevsky #2 (P2 in Fig.1) was registered with a pair of temperature and pressure loggers HOBO U20-001-04. One of the loggers - U20-001-04 was used to record atmospheric pressure, the other – to register temperature at the spring outflow (recording rate 20 min^{-1}). Analysis result of continuous observations 2009-2010 at Pinachevsky spring #2 revealed short-term (+0.5°C during 8 hours) co-seismic temperature reaction on earthquake 30.07.2010 with a magnitude 6.6 in Avacha bay (Fig. 5 b).

At Pinachevsky spring #1 (P1 in Figure 1) in 2010-2013 we recorded changes in temperature and conductivity (HOBO U24-001) of pouring water (conductivity reflects changes in water salinity) (recording rate of 30 min^{-1}). We discovered contrast prolonged post-seismic response to a swarm of earthquakes with a magnitude of 6.4-6.9, occurring 28.02 - 01.03.2013 in southern Kamchatka (fig.5 c): increase in temperature of 0.6 °C and in conductivity from 224 to 381 µS/cm.

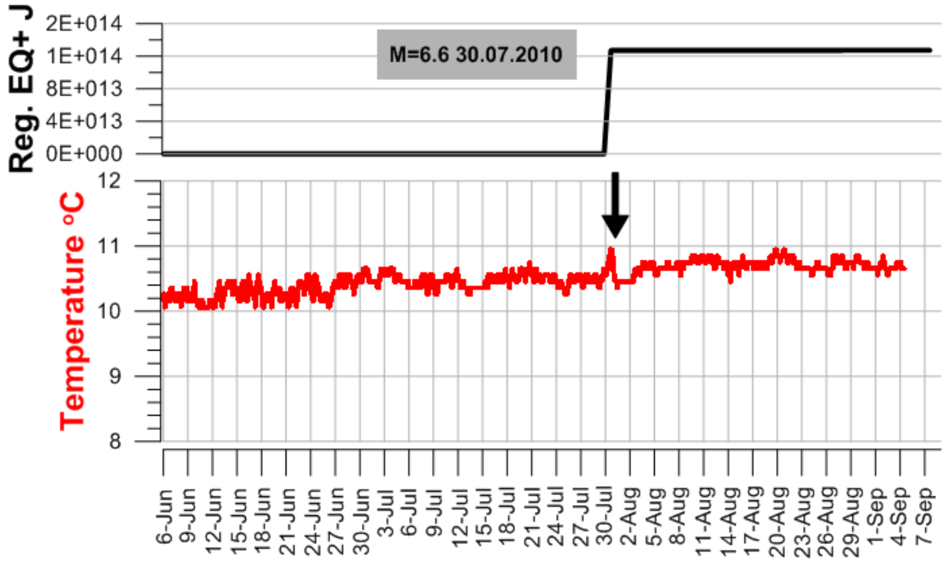

Figure 5 b: Pinachevsky-2 spring (P2 in Figs.) response to earthquakes swarm M=6.6 30.07.2010 in Avachinsky Bay.

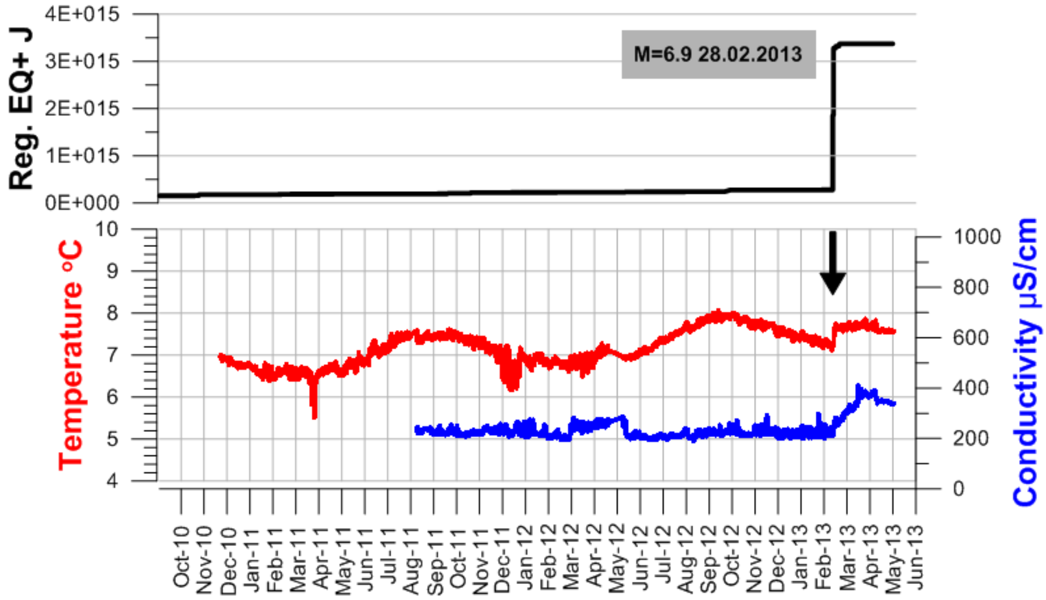

Figure 5c: Pinachevsky-1 spring (P1 in Fig. 1) response to earthquakes swarm M=6.4-6.9 on February 28 – March 1, 2013 in South-Eastern Kamchatka.

At Izotovsky spring (IS in Fig. 1) (50 °C, 7 km from Koryaksky volcano) in 2010-2013 we conducted continuous monitoring of temperature with a T - logger (HOBO U12) (recording rate 15 min^{-1}). We discovered temperature rise of 6-12 °C in the period 10.2011-06.2012 compared with the average monthly maximum temperatures after activation of seismic activity (nine MEQs with magnitudes of 0.75-2.95) in the Koryaksky volcano area on 2.08.2011 (Fig. 5 d). Average temperature rise of 0.5 °C in Pinachevsky spring in 2012 compared to 2011 (Fig. 5 b) can also be associated with the effect of enhancing seismic activity of Koryaksky volcano. Estimated MEQs swarm plane area ~ 1 x 1.5 km is located 1.5 km SW from Isotovsky springs at elevations -3 - -2 km and has a dip angle 45^{o} and dip azimuth 118^{o} (ESE) (see Fig.2 for details).

At flowing well 53 (Bystrinsky aquifer, well depth of 290 m (-128 m abs.) in 2010-2013 we conducted continuous temperature monitoring with T - logger (HOBO U12) (recording rate 15 min^{-1}). Temperature remained virtually unchanged at 4.3-4.4 °C during the entire period of record.

4. HYDRODYNAMIC MODELING OF THE AVACHINSKY-KORYAKSKY BASIN

4.1 Hydrodynamic Model Setup.

The model includes three main layers, corresponding to aquifer complexes of Koryaksky-Avachinsky volcanoes group structures (Q_{3-4}), embedded artesian-volcanogenic basin (AVB) and Neogene lower-Quarternary deposits (N-Q_{1-2}), Cretaceous basement (K_2) (Fig. 6). At zoning of model layers, we assigned the domains of magmatic volcano feeding system, determined according to seismic data (reservoirs “K” and “A”) inside of the embedded artesian-volcanogenic basin, Pinachevsky extrusions (lava-tuffaceous and vent) and the host rock domains. Polygonal mesh numerical model includes 18730 elements. On the model boundaries, crossing the Pacific Ocean coastline, rivers Avacha and Nalycheva, we set the conditions of groundwater discharge - constant pressure (1 bar). On the volcanoes’ surface we set a condition of continuous saturation of the air phase (0.8). Infiltration recharge is set in the inner elements of volcano structures above 2000 m.a.s.l.

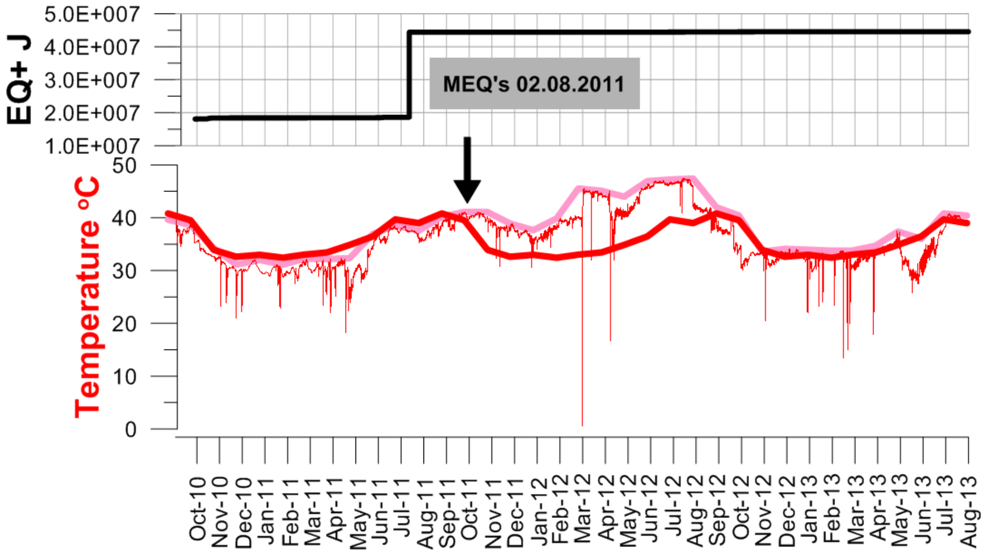

Figure 5d: Isotovsky hot spring (IS in Fig.1) response to local seismicity MEQs in Koryaksky volcano. Thick red line is a season averaged max temperature in each month, thick pink line is a max temperature in each month, thin pink line is recorded data.

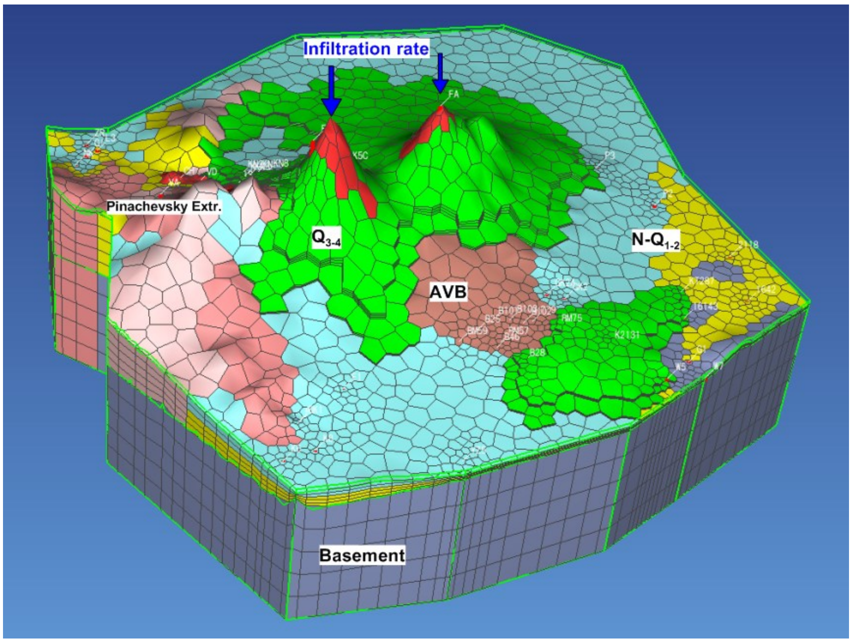

Figure 6: Parametrization of the 3D hydrodynamic model of the Avachinsky-Koryaksky volcanogenic basin. Estimated parameters are shown with explanation in parentheses.

4.2 Parameterization and Calibration of the Hydrodynamic Model

Calibration was accomplished by inversion iTOUGH2-EOS9 modeling to reproduce the steady hydrodynamic state (assumed for the time of 5 thousand years) in the Koryaksky-Avachinsky volcanogenic basin. Module EOS9 allows to reproduce the unsaturated conditions, appropriate to the cones of volcanic structures. To calibrate the model, we used the data on groundwater levels in 13 wells, which are translated to values of pressure at the centers of model elements, relevant to well bottoms at given the salinity by hydrostatic formulas (Fig. 7).

At the first stage of modeling, we disabled Cretaceous basement and Neogene-Quaternary complex (as having negligibly low permeability). As a result of inversion modeling we estimated rates of infiltration recharge (Koryaksky and Avachinsky volcanoes) and AVB permeability. At the second stage of modeling we included into the model Cretaceous basement and Neogene-lower Quaternary complex (10^{-3} mD permeability), and performed inversion modeling for 5000 years (effective infiltration time out of volcano structures, given the history of their existence). Infiltration recharge rate was used as an estimated parameter. Given the impossibility of obtaining the model match with regard to the wells of Neogene-lower Quaternary complex (K6, K8, E1, R2, R3) was characterized by low pressures, we had to introduce into the model another estimated parameter - compressibility. Anomalously low pressure values of well R2 led to a higher rating of compressibility of Neogene-lower Quaternary complex in the area of the relevant well (6.7 10^{-6} Pa^{-1}). In addition, to ensure matches with observational data in the area of Ketkinsky geothermal field (wells K6 and K8) we had to set an additional deep upflow source on the model.

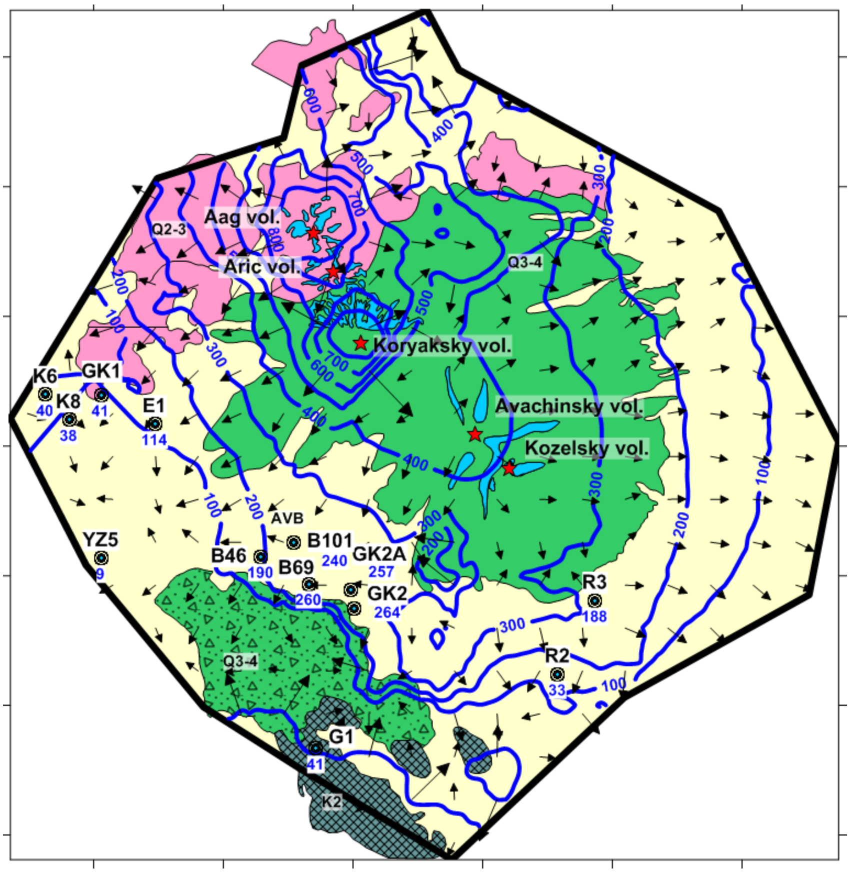

Figure 7: Hydrodynamic modeling (TOUGH2-EOS9) ground waters level (masl) and flows (arrows) distributions in Koryaksko-Avachinsky volcanogenic basin. Wells used for model calibration are shown by circles with numbers (black) and static water levels (blue). Axis scale is 10 km.

In the best version of the inversion modeling (#8D2-EOS9) we obtained matches in the 13 calibration deep wells with standard deviation of 1.4 bar and bias of 0.2 bar. The total rate of infiltration recharge (Koryaksky and Avachinsky volcanoes) was estimated at 5880 kg/s, AVB permeability was 2.0-3.0 D. Fig. 6 shows model distribution of static groundwater level and groundwater flows.

4.3 Discussion of the Results

Conceptual hydrogeological model, underlying the modeling version, is generally confirmed by the total water balance and hydrochemical data. The estimated weight of water within the model region of the Koryaksky-Avachinsky volcanogenic basin is assessed to be $0.59 \cdot 10^{15}$ kg. This corresponds to the time of complete water exchange in the reservoir in the first thousand years. Sodium chloride water with salinity of 10-20 g/l, which are widespread in the basement, indicates the absence of substantial infiltration into the basement rocks.

5. MAGMA CHAMBERS GEOTHERMAL POTENTIAL AND METHANE CH_4 RESERVOIRS

There is geological and geophysical background to approximate the geometry of the magma chamber of ellipsoid shape beneath Avachinsky volcano (S.A. Fedotov, 2006): the position of the upper edge of the magma chamber is estimated to be within the range of elevations of 0 - -2 km, the size of horizontal and vertical axles of the ellipsoid along the isotherm 900°C is not less than 2.3 and 1.53 km, 700°C isotherm - 4.5 km, and 3 km, respectively. Given the duration of underground circulation system operation for 100 years, the unit of heated rocks with volume of about 50 km3 can produce about 250 megawatts of electricity (S.A. Fedotov, 2006). Currently, the above estimates are specified, based on the actual geometry and heat transfer conditions of recharge volcano magmatic systems with host rocks.

Energy potential of the Avachinsky and Koryaksky volcanoes magma chambers may be significantly added by hydrocarbon accumulation in adjacent Neogene - Quarternary layer (Fig. 8). Methane saturated reservoirs were penetrated by wells R3, E1, K1, K6, K8 in Neogene - Quaternary layer at the south-eastern and south-western foothills Koryaksky and Avachinsky volcanoes, and

Pinachevsky extrusions. Those reservoirs may be formed as a result of heat exchange from magma emplacement reservoirs beneath volcanoes into hosted gas hydrates and organic sediments. The area of potential methane accumulation is accounted ~650 km^2, that is equivalent of ~390 billion m^3 of gas resources (if western Kamchatka gas fields analog production parameter estimates used). At least 15% of the area above has road and drilling access, hence significant gas resources are available for production.

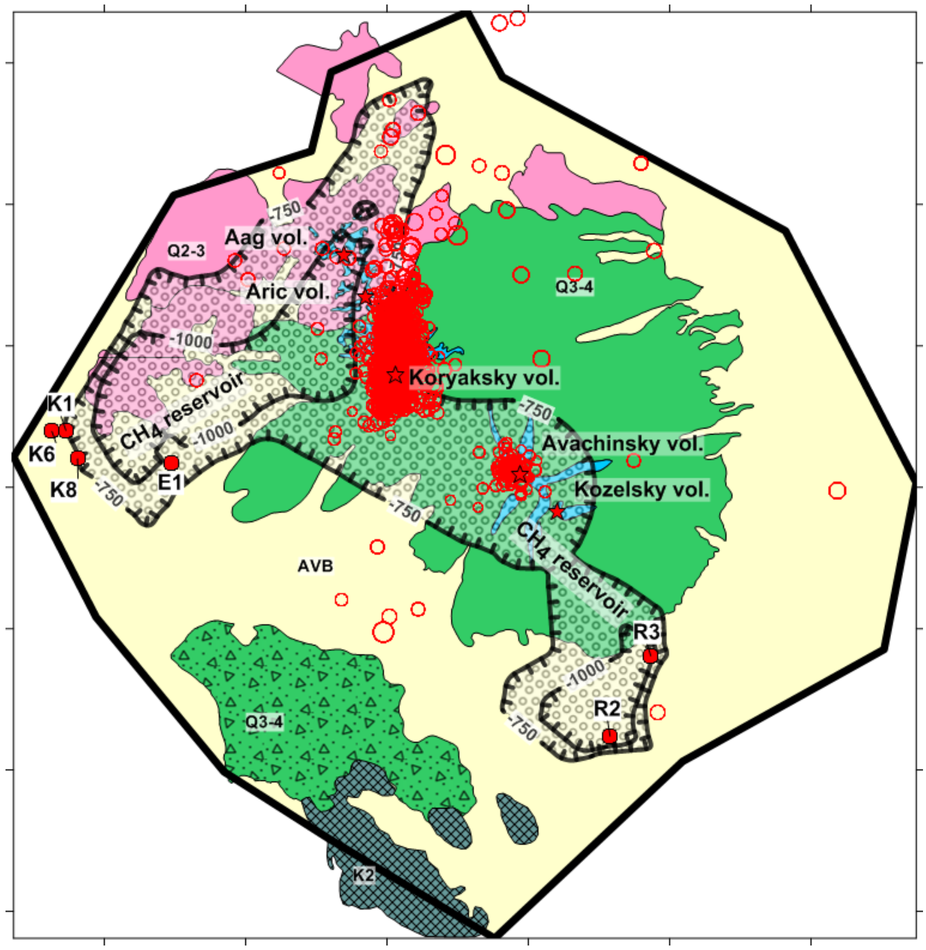

Figure 8: Koryaksky-Avachinsky volcanogenic basin potential geothermal and gas (methane) reservoirs. Top of Cretaceous basement is shown by hatched isolines (-750 and -1000 m.a.s.l.). Potential geothermal reservoirs, magma emplacement zones beneath Koryaksky and Avachinsky volcanoes, are shown by red circles of MEQs epicenters (2009, KF GS RAS). Potential gas (methane) reservoirs, area of methane distribution confirmed be wells (R3, K1, K6, K8, E1) within a basin above a sink part of the Cretaceous basement (deeper than -750 m.a.s.l.), are shown in area with grey circle limited by hatched line). Axis scale is 10 km.

CONCLUSIONS

1. Isotope composition (δD, $\delta^{18}O$) of the thermal mineral springs (Koryaksky Narzans, Isotovsky and Pinachevsky) and wells of the Bystrinsky aquifer pointed out water recharge took place from +2000 - +2500 m.a.s.l. at glaciers on summits of Koryaksky and Avachinsky volcanoes, while Chistinsky Narzans fed from central part of Pinachevsky extrusions (Aric and Aag volcanoes) at elevations of 800-1500 m.a.s.l. Isotope composition $\delta^{13}C$ in CO_2 sampled from Koryaksky Narzan and Isotovky revealed its magmatic origin. Thus CO_2 springs in NW foothills of Koryaksky volcano are formed as a result of mixing of magmatic gases and melting glaciers waters.

2. Thermal mineral springs adjacent to Koryaksky volcano and Pinachevsky extrusions showed sensitivity to seismic events: post-seismic temperature, flowrates, water salinity and methane concentration rise in connection to earthquakes with magnitude 6.6-6.9 in South-East Kamchatka, temperature increase after MEQ's swarms in Koryaksky volcano. This is pointed out on hydraulic connection between magma emplacement zone beneath Korykasky volcano (reservoir "K"), adjacent hydrothermal systems and methane reservoirs.

3. 3D hydrodynamic TOUGH2-EOS9 model of the Avachinsky-Koryaksky volcanogenic basin was developed and calibrated based on water levels in 13 deep hydrogeological wells. Inverse modeling was used to estimate infiltration rate in basin recharge area (~ 6 m^3/s), water level surface elevations beneath Koryaksky and Avachinsky volcanoes (max +900 m.a.s.l. and +400 m.a.s.l.) and compressibility of Neogene - Quaternary layer ($9.4\ 10^{-7}$ - $6.7\ 10^{-6}$ Pa^{-1}). Higher compressibility values may reflect local gas saturation conditions.

4. Magma emplacement zones are clearly detected by local earthquakes distributions below Koryaksky and Avachinsky volcanoes are potential targets for geothermal exploration. Shallow methane CH_4 reservoirs penetrated by wells in Neogene - Quaternary layer

around Koryaksky and Avachinsky volcanoes, and Pinachevsky extrusions may be formed as a result induced magma-hydrothermal gas generation from volcanoes basement organic-reach sediments. The area of potential methane accumulation with significant gas resources is estimated ~650 km^2.

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