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GEOTHERMAL ENERGY TRANSPORT IN RECENT VOLCANISM AREAS (KAMCHATKA AND KURILE ISLANDS) : SOME EXAMPLES AND CONCEPTUAL MODEL

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ABSTRACT

Geothermal energy transported to earth surface through volcanoes and hydrothermal systems. Based on numerical model analysis of deep drilling and exploitation data of some Kamchatka and Kurile Islands geothermal reservoirs , and heat and mass flow rates estimations of some Kamchatka volcanoes , the following conceptual model of geothermal energy transport is suggested : if magma trapped in upper crust – hydrothermal system occur, if magma reached earth surface – volcano occur. The consequence is: active volcanoes (discharging magma) are not a promising target for geothermal wells drilling. Some examples of existing Kamchatka and Kurile Islands geothermal fields are following as examples.

INTRODUCTION

The average mass rate of volcanoes is estimated based on volume of volcano and age of volcano (tephrohronological method) [20, 4, 7]. As a result , geothermal energy transport rate of volcano is derived based on magma enthalpy about 1 MJ/kg.

Geothermal energy transport rate , e.g. heat and mass flowrate of fluids feeding geothermal reservoirs are estimated based on numerical models of geothermal reservoirs , calibrated on natural state conditions and flowtests and exploitation matches.

Figs. 1 and 2 shows space distribution of volcanoes and hydrothermal systems of Kamchatka and Kurile Islands , and Fig.3 (corresponding Tables 1 and 2) shows geothermal energy transport rate of some volcanoes and hydrothermal systems .An average estimations of geothermal energy transport rate of volcanoes and hydrothermal systems are close : 250 MW and 127 MW , correspondingly. Due to this , the following questions arises: 1. What is the mechanism of geothermal energy transport in upper crust of recent volcanic areas? 2. What are possibilities of geothermal energy use , following such mechanism ?

GEOTHERMAL ENERGY TRANSPORT IN VOLCANOES AND HYDROTHERMAL SYSTEMS

Volcanoes

Geothermal energy transported by magma through volcano feeding channels or dykes. The simple model of magma flow through pipe based on Fanning equation [22] :

$$\Delta P/\Delta z = f(Re)\, G^2 / (4\, \rho_m\, r)$$

- gives volcano feeding channel radii «r» in a range of 0.5 – 2.0 m , if magma viscosity assumed to be in a range $1.3\ 10^2 – 6.1\ 10^4$ Pa*s ,magma mass flow rates «G» corresponding to Fig.3 and pressure gradient «$\Delta P/\Delta z$» corresponding to a few hundred of bars on a 100 km. That mean the most of geothermal energy transported through volcanoes released on or near of the earth surface.

Hydrothermal Systems

Geothermal energy transported mainly by water. Fig.4 and Table 3 shows where this water came from: in most cases in Kamchatka this is a meteoric origin water coming from up-hills recharge areas [7, 13 ,17 ,21] Low viscosity of water 0.2-1.4 10^{-3} Pa*s allow to penetrate it from recharge areas to deeper hot magma body containing parts of earth crust , using relatively narrow channels due to pressure gradients , caused by thermal lift pressure drop (up to 100 bars) occurred in a bottom of ascending hot water fluid flows [7 , 8] .

Fig.1 Kamchatka volcanoes (triangles) and hydrothermal systems (circles) . Hydrothermal systems:1-Koshelevsky,2-Pauzhetsky,3-Hodutkinsky, 4-Mutnovsky,5-Bolshe-Banny,6-Paratunsky,7-Malkin sky, 8-Karymsky,9-Semyachiksky, 10-Geysers Valley, 11-Uzon, 12-Essovsky, 13-Apapelsky, 14-Kireunsky(see also Tables 1 and 2 attached)

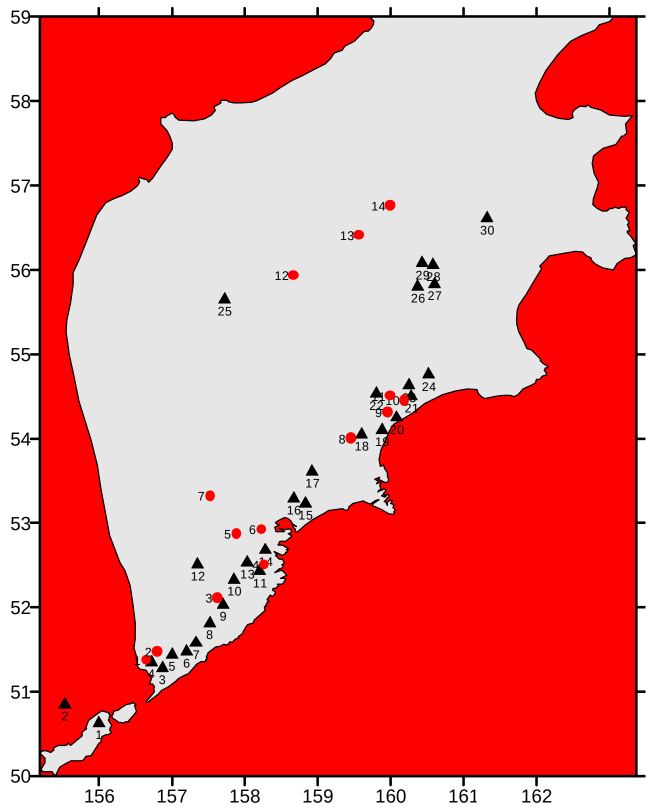
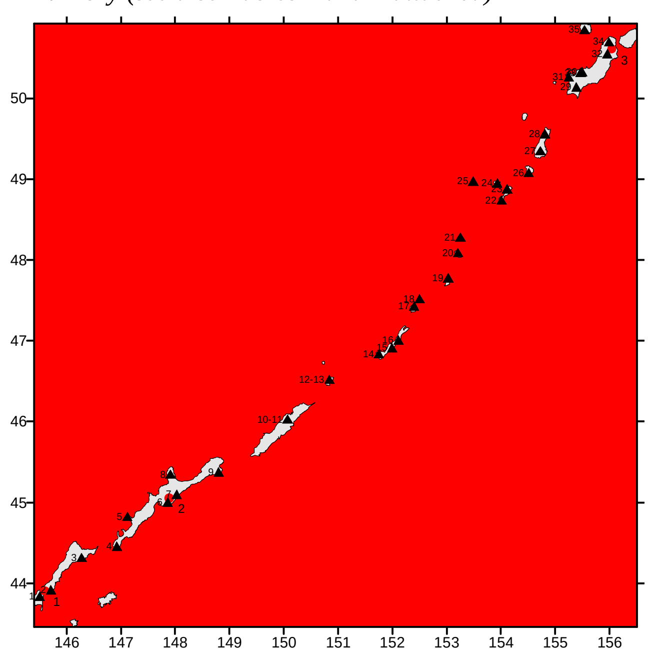


Fig.2 Kurile Islands volcanoes (triangles) and explorated geothermal fields (circles). Geothermal fields: 1- Goryachy Plyazh, 2- Oceansky, 3- Severo-Kurilsky (see also Tables 1 and 2 attached)



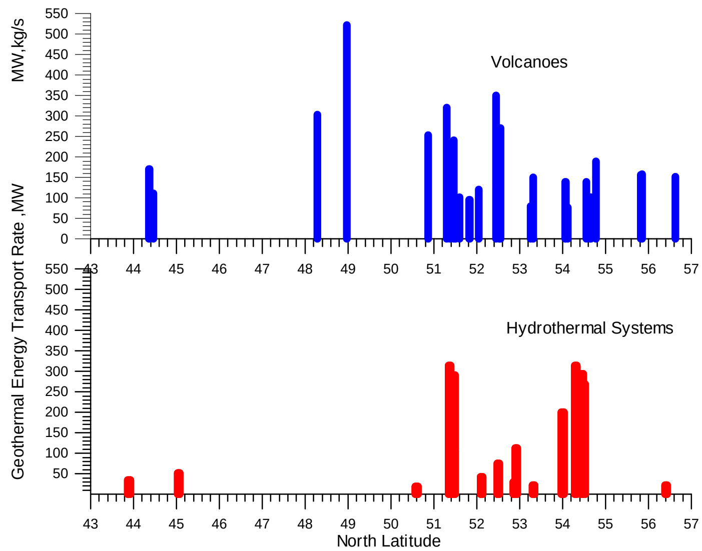


Fig.3 Geothermal energy transport rate of some Kamchatka and Kurile Islands volcanoes (except of Kluchevskoy) and hydrothermal systems (see Tables 1 and 2 attached)

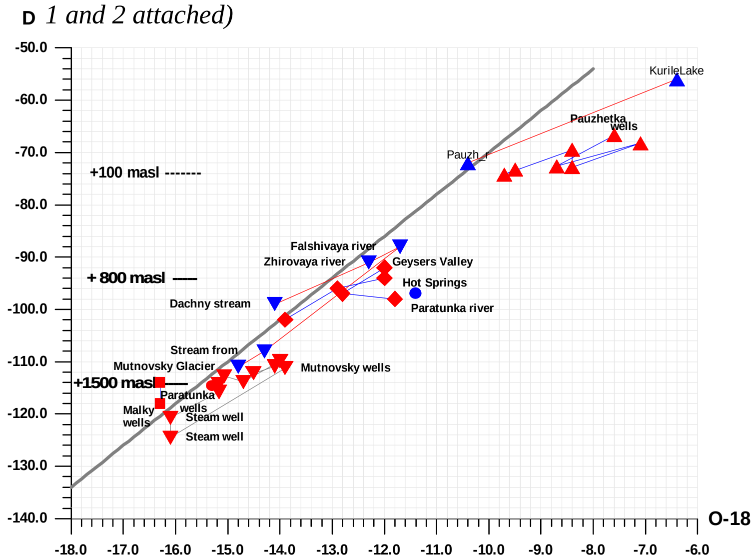


Fig4 Fluid (water) recharge conditions of Kamchatka hydrothermal systems based on hydroisotope (D,O-18) data. See Table 3 attached.

EXAMPLES OF GEOTHERMAL FIELDS

Paratunsky Geothermal Field (Kamchatka) [12]

It was shown in [12] temperature distribution at –1000 masl. and intrusive complex of neogene age top surface distribution. At this elevation three roots of hot ascending flows associated with the boundaries of the intrusive diorites body are clearly observed . These flows enter sub-horizontal layers at –1000 masl and are feeding Sredny , Nizhny and Severny geothermal reservoirs , which occur in andesite tuffs (so called "green tuffs" formation) . The elevation where ascending hot flow is diverted to lateral outflow (the bottom of the "green tuffs" reservoir) is detected by plotting normalized cumulative rate (e.g. total rate obtained at specified depth divided by number of wells drilled) of the well vs depth, based on data obtained during drilling Normalized rate is zero in the intervals from 0 to 100 – 150 m depth (upper caprock) , then increased from 0 up to 17-25 kg/s in the intervals from 100-150 m up to 1200 m depth ("green tuffs " reservoir) , then slowly increased on 1-4 kg/s by 2500 m depth (relatively impermeable basement rocks) . Modeling natural state conditions and exploitation of geothermal field (TOUGH2 , 1- layer "well by well" model used) shows the following mass flow rates and permeabilities:

Site	Mass flowrate kg/s	Enthalpy kJ/kg	Permeability mD
Sredny	138	360	90
Nizhny	95	95	60
Severny	60	60	60
Ambient reservoir			50-60

So , geothermal energy transport rate in that case is estimated as 110 MW. It was found also seasonal variations of ascending mass flow rate (modeling based estimations are: +- 5% , summer increase , winter decrease).

Malkinsky Geothermal Field (Kamchatka) [3]

Ascending hot fluid flow in Malkinsky field has a temperature 80 ^{o}C and occures in a "tube" 80^{o} South-East dip and horizontal cross section area is around 0.17 km2 . Reservoir rocks containing upper cretaceous volcanogenic rocks and shists , intruded by neogene magmatic complexes. Based on modeling natural state conditions and exploitation 1991-94 (TOUGH2 , 3D rectangular model used) the mass flow of ascending hot fluid flow with enthalpy 380 kJ/kg is estimated as 59 kg/s (22 MW) , and "tube" permeability 300 mD with ambient rock permeability 3 mD.

Pauzhetsky Geothermal Field (Kamchatka)

Upper Pleistocene magmatic extrusions complex (dacites) is in charge of structure control of heat feeding and pearmeability distributions in Pauzhetsky geothermal field . This magmatic complex is inside of temperature anomaly zone above 190 ^{o}C. The main zone of ascending hot fluid flow with enthalpy about 830-920 kJ/kg is localized in poligon restricted by wells RE6 , 131 , 23, 109. Production intervals distribution analysis is represented by normalized cumulative rate graph . Production interval includes a number of production zones (in average 4.3), and average thickness of production interval is 334 m. Most of production intervals occures at depth 100 – 800 m , where Pliocene - lower Pleistocene "green tuffs" type reservoir was encountered. Based on preliminary results of numerical modeling (1- layer "well by well" model) hot fluid ascending flows is estimated as 330 kg/s (290 MW).

Mutnovsky Geothermal Field (Kamchatka) [8 , 9 , 10]

High temperature ascending fluid flows in Mutnovsky geothermal field : "Main" and "North-Eastern" , and meridional cross-section are shown in [8,9]. These flows are fixed by temperature isoline 300 ^{o}C at –750 masl. "Main" up-flow zone occur at south-east boundary of diorite intrusion , which penetrated by wells at depth 1.5 – 2 km. This intrusion seems responsible for heat feeding and permeability distribution in geothermal reservoir. Although 3-5 mD average permeability values in 240 ^{o}C ambient reservoir were estimated based on numerical modeling , it was found double-porosity nature of production zones. Double-porosity parameters are : fracture permeability 0.45 – 9 mD, fracture spacing – 25 – 200 m , fracture/matrix volume ratio – 0.01 – 0.0002 . Real geometry of production zones was identified in some cases, while this information not published yet. Meteoric water recharge in Mutnovsky hydrothermal system occur due to melting of the glacier in the crater of Mutnovsky volcano, located 8 km SSW. Total mass flowrate of ascending high temperature (1270 – 1390 kJ/kg) fluid flows is estimated as 54 kg/s (based on TOUGH2 , 3D rectangular grid model), so the total geothermal energy transport rate is estimated as 72 MW.

Oceansky Geothermal Field (Kurile Islands) [11]

Oceansky geothermal field located in Iturup Island (Kurile Islands) . Production field occur in submeridional zone on south-west slope of Baransky volcano . Reservoir rocks are tuffs and lavas dacite composition , overlaid by Quaternary sedimentary and volcanogenic rocks. Geometry and permeability estimations of so called "Dvoinikovo-Kipyashy" production zone, penetrated by wells 51 , 52 , 53 , 57 , 60 , are based on numerical modeling (TOUGH2 , 3D rectangular grid model) are the following: permeability 15-30 mD, vertical thickness and meridional length > 1500 m , latitudional thickness 500 m and permeability of ambient rocks less than 3.5 mD. Double–porosity nature characterized production zones, parameters are the following: fracture permeability 3.6 – 30 mD , fracture spacing 2- 100 m , fracture porosity 0.0002 – 0.02. Production zone temperature is up to 280 ^{o}C. Based on modeling, mass flow rate of ascending hot fluid flows is estimated as 35 kg/s with an enthalpy 1470 kJ/kg , so 52 MW is geothermal energy transport rate estimation.

Goryachy Plyazh Geothermal Field (Kurile Isl.) [2]

Geothermal field located north-east of Mendeleev volcano (Kunashir Isl., Kurile Islands) , reservoir composed of volcanogenic rocks of neogene age. Production zone strike in north-east direction and north-west dip (geometry parameters are: length – 1000 m , width 300-640 m , depth 400 m and horizontal cross section area is about 0.5 km^2 . Temperature of fluid 180-190 ^{o}C , 1.7 year flowtests demonstrated 40-50 kg/s as a possible stable yield of the geothermal field. Thus , geothermal energy transport rate of this field may be estimated as 30 – 40 MW.

Severo-Kurilsky Geothermal Field (Kurile Isl.) [14]

Three deep exploration wells and a number of shallow wells were drilled there. Well P-2 penetrated production reservoir (neogene tuffs) in a depth interval 400-840 m (flowrate 8.5 kg/s , thickness-permeability 1.65 D*m , production zone temperature more than 105 ^{o}C) . Production zone characterized by relatively high (2x) gamma activity of rocks in the interval 450-700 m , which may reflect existence of sub-volcanic magmatic bodies , responsible for reservoir formation. Frequency soundings reveals 2 Ohm*m anomaly at –300 - -500 masl interval and cross section area 0.18 – 0.57 km2 associated with hot fluid ascending up-flow. Numerical modeling of the natural state conditions shows mass flow rate of ascending hot fluid flow in a range 30-40 kg/s with corresponding enthalpy 445-466 kJ/kg (TOUGH2 , simple 1-D radial model used) . That's corresponds to 13-19 MW of the geothermal energy transport rate.

CONCLUSIONS : CONCEPTUAL MODEL OF VOLCANIC AND HYDROTHERMAL ACTIVITY

Close values of geothermal energy transport rate in volcanoes and hydrothermal systems, and meteoric (non-magmatic) origin of working fluid in hydrothermal systems allow to suggest the following conceptual model (Fig. 5): if magma trapped in upper crust – hydrothermal system occur and no volcano , if magma is going through – volcano occur and no hydrothermal system.

Conceptual model above was confirmed by some examples of existing Kamchatka and Kurile Islands geothermal fields .

The consequence is: active volcanoes (discharging magma) are not a promising targets for geothermal drilling.

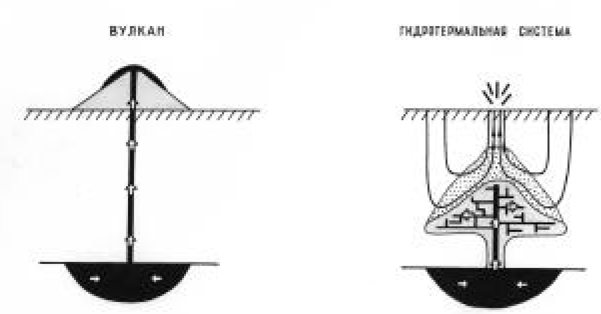


Fig 5 Conceptual model of geothermal energy transport in recent volcanism area.

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Table 1. Geothermal energy transport rate in Kamchatka and Kurile Islands hydrothermal systems , # - corresponding to Figs.1 and 2.

Hydrothermal system	#	E	N	MWt	Ref.
Pauzhetsky	2	156.8	51.47	290	
Koshelevsky	1	156.65	51.37	314	[26]
Hodutkinsky	3	157.63	52.11	42	[5]
Mutnovsky	4	158.27	52.5	75	[10]
Paratunsky	6	158.23	52.92	112.5	[12]
Bolshe-Banny	5	157.89	52.87	30	[16]
Malkinsky	7	157.53	53.32	22	[3]
Karumsky	8	159.46	54	200	[19]
Semyachiksky	9	159.96	54.31	314	[1]
Uzon	11	160	54.5	268	[15]
Geyser	10	160.19	54.45	294	[25]
Essovsky	12	158.67	55.93		
Appapelsky	13	159.57	56.41	16	[18]
Kireunsky	14	160	56.76	22	[6]
GorychyPlyazh	1	145.6	43.9	35	[2]
Oceansky	2	147.9	45.1	52	[11]
SevKurilsky	3	156.1	50.6	19	[14]
Average:				121.0	

Table 2. Geothermal energy transport rate (MWt or kg/s) in Kamchatka and Kurile Islands volcanoes, # - corresponding to Figs.1 and 2.

Volcano (Kuriles Isl.)	#	E	N	MWt	Ref
Golovnin	1	145.51	43.84		
Mendeleev	2	145.71	43.92		
Tyatya	3	146.28	44.32	171	[20]
Beratarube	4	146.93	44.46	111	[20]
Atsonopuri	5	147.12	44.83		
I-Grozny	6	147.86	45.00		
Baranskogo	7	148.03	45.10		
B-Hmelnitsky	8	147.92	45.35		
Kudryavy	9	148.80	45.38		
Trezubets+Berga 10 -	11	150.07	46.03		
Chernogo+Snow 12 -	13	150.84	46.52		
Goryashaya Banka	14	151.75	46.84		
Zavaritskogo	15	152.00	46.91		
Prevo	16	152.11	47.01		
Ketoy		152.40	47.30		
Pollasa	17	152.40	47.43		
Ushishir	18	152.50	47.52		
Rashua	19	153.03	47.78		
Sarycheva	20	153.21	48.09		
Raikone	21	153.25	48.28	304	[20]
Kuantomintar	22	154.01	48.74		
Sinarka	23	154.11	48.88		
Ekarma	24	153.93	48.95		
Chirinkotan	25	153.49	48.97	523	[20]
Severgina	26	154.51	49.08		
Krenitsina	27	154.73	49.35		
Nemo	28	154.81	49.56		
Karpinskogo	29	155.39	50.14		
Fussa	31	155.25	50.27		
Chikurachki	33	155.47	50.32		
Vernadskogo	32	155.96	50.55		
Ebeko	34	156	50.68		
Alaid	35	155.53	50.87	254	[20]

Volcano (Kamchatka)	#	E	N	MWt	Ref
Ebeko	1	156	50.68		
Alaid	2	155.53	50.87	254	[20]
Kambalny	3	156.87	51.3	320	[4]
Koshelevsky	4	156.72	51.37	135	[4]
DikyGreben	5	157	51.46	240	[4]
Ilinsky	6	157.2	51.5	95	[20]
Zheltovsky	7	157.33	51.6	102	[20]
Ksuduch	8	157.52	51.83	95	[20]
Hodutka	9	157.7	52.05	120	[20]
Asacha	10	157.85	52.35		
Mutnovsky	11	158.2	52.45	350	[4]
Opala	12	157.35	52.53	156	[20]
Gorely	13	158.03	52.55	270	[4]
Viluchinsky	14	158.28	52.7		
Avacha	15	158.83	53.25	80	[20]
Koryaksky	16	158.67	53.31	150	[20]
Dzendzur	17	158.92	53.63		
Karumsky	18	159.6	54.07	140	[20]
Mal-Semychik	19	159.88	54.12	76	[20]
Bol-Semyachik	20	160.08	54.27		
Kihpinych	21	160.28	54.52		
Taunshits	22	159.8	54.55	140	[20]
Krasheninnikova	23	160.25	54.65	102	[20]
Kronotsky	24	160.52	54.78	190	[20]
Ichinsky	25	157.72	55.67		
Plosky-Tolbachik	26	160.37	55.82	156	[20]
Bezymyanny	27	160.6	55.85	158	[20]
Kluchevskoy	28	160.58	56.08	1904	[20]
Ushkovsky	29	160.43	56.1		
Shiveluch	30	161.32	56.63	152	[20]
Average:				249.6	

Table 3 . Summary of D and O18 data of some Kamchatka and Kurile Isl. Geothermal Fields.

Mutnovsky geothermal field [13]	δD	δO-18	Notes:
Dachny stream	-99.0	-14.1	
Zhirovaya river	-91.0	-12.3	
Falshivaya river	-88.0	-11.7	
Stream from	-108.0	-14.3	
Mutnovsky Glacier	-111.0	-14.8	
049N	-109.9	-14.0	2-Phase well
O14	-113.9	-14.7	2-Phase well
O1	-112.8	-15.1	2-Phase well
1	-114.3	-15.2	2-Phase well
24	-115.8	-15.2	2-Phase well
O16	-120.7	-16.1	Steam well
26	-124.5	-16.1	Steam well
O29W	-111.3	-13.9	2-Phase well

Pauzhetsky geothermal field [7 , 13]	δD	δO-18	Notes;
120	-73.3	-9.5	2-Phase well
106	-74.2	-9.7	2-Phase well
16	-69.5	-8.4	2-Phase well
108	-72.8	-8.4	2-Phase well
RE1	-68.2	-7.1	2-Phase well
20	-72.6	-8.7	2-Phase well
15	-66.7	-7.6	2-Phase well
Pauzhetka river	-72.0	-10.4	
KurileLake	-56.0	-6.4	

Paratunsky geothermal field [21]	δD	δO-18	Notes;
Severny Site	-116.8	-15.9	Hot wells
Nizhne-Paratunsky	-115.5	-15.6	Hot wells
Sredny Site	-111.5	-14.5	Hot wells
Average (wells):	-114.6	-15.3	Hot wells
Paratunka River	-97.0	-11.4	

Geysers Valley geothermal field [13]	δD	δO-18	Notes;
G1	-102.0	-13.9	Hot spring
G2	--96.0	-12.9	Hot spring
G3	--94.0	-12.0	Hot spring
G4	-92.0	-12.0	Hot spring
G5	-97.0	-12.8	Hot spring
G6	-98.0	-11.8	Hot Spring

Severo – Kurilsky geothermal field [14]	δD	δO-18	Notes;
P2	-82.0	-7.4	Hot well
Matroskaya river	-92.5	-12.4	
Ocean	-70.0	-9.8	200 m from shore

Malkinsky geothermal field [17]	δD	δO-18	Notes;
Hot wells (averaged):	-114.0	-16.3	
Kluchevka River	-118.0	-16.3	