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Geological Conditions, Exploitation History and Near Future Possibilities of Geothermal Development in Kamchatka, Russia

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ABSTRACT

This study shows that geothermal resources development in Kamchatka is possible in two main applications: generation of electric energy at high-temperature geothermal fields and heat supply through the use of low-temperature geothermal fields. The Kamchatka geothermal resources are estimated to be sufficient for generating electricity with a capacity of up to 3,900 MWe. The geothermal resources for heat supply are estimated at about 1350 MWh. The use of numerical thermo-hydrodynamic TOUGH2-modeling with exploitation forecast of productive geothermal reservoirs with known reservoir and energy properties shows as follows: (1) The possibility of increasing the electrical productivity of the already exploited areas of the Mutnovsky geothermal field up to 105 MWe, the Pauzhetsky geothermal field to 11 MWe by using binary technologies; (2) The possibility of increasing heat generation during the operation of the Paratunsky geothermal field with submersible pumps up to 216 MWt, which ensures heat consumption for Petropavlovsk-Kamchatsky centralized heat supply systems. Further prospects for increasing geothermal electricity and heat supply in Kamchatka may also be associated with the exploration of partially explored Bolshe-Banny, Nizhne-Koshelevsky and Verkhne-Paratunsky geothermal fields. The use of geothermal resources of the latter for energy purposes in combination with the increase in capacity of the Mutnovsky GeoPP and the Pauzhetskaya GeoPP solves the problem of reliable and complete power supply of the Kamchatka south and center at the expense of geothermal energy sources. Geothermal reservoirs with hydrothermal circulation associated with the magmatic feeding systems of the Mutnovsky and Koryaksky volcanoes may also be considered as targets for exploratory drilling for geothermal energy. Paratunsky LT geothermal field case study. Chemical history 1966-2019 of the Paratunsky LT exploitation reveals chloride waters inflows from E & NE boundaries continues, trends of siginificant SiO_2 geothermometer rise (up to 15-20°C), while Na-K & Na-K-Ca geothermometers decline (down to 25-30°C), in SR Site pH decline too. Using secondary minerals distributions data of recently drilled well RE-10 and water chemistry data of P geothermal reservoir, groundwater reservoir and SC chloride water reservoir – a lamped TOUGHREACT model was developed and used to explain geothermometers transient trends observed. Modeling shows calcite and smectite-Ca generation rate increase, quartz dissolution rate decrease after exploitation started. In combination with boundary waters inflows mixing, this is may cause geothermometers trends observed during 60Y exploitation.

1. INTRODUCTION

This article considers **geothermal resources** as sources of formation of geothermal energy extracted by wells, **identified geothermal** resources as possible useful (converted into mechanical energy for high-temperature systems or consumed in the form of thermal energy for medium and low-temperature systems) fraction of the heat discharge of exploitation wells (MWh). When assessing geothermal resources, hydrothermal systems are divided into high-temperature (temperature in the depths more than 150 ° C), medium-temperature (with a temperature from 90 to 150 ° C) and low-temperature (with a temperature less than 90 ° C) (Muffler, 1979, p.1).

A characteristic feature of Kamchatka's geothermal conditions and geothermal resource formation is the extensive development of local thermoanomalies associated with modern or active volcanic activity, characterized by intensive processes of hydrothermal alteration of rocks, mineral formation and anomalously high heat and substance yield to the surface. Considering mainly the geothermal resources of high-temperature hydrothermal systems which are now being actually used or may be used in geothermal power plants, we give a general assessment of other types of Kamchatka's geothermal resources: low and medium temperature hydrothermal systems, petrogeothermal resources, including heat resources of rocks of shallow magmatic chambers.

In volcanic areas, thermal springs and other surface thermal manifestations are indicators of the presence of hydrothermal systems (productive geothermal reservoirs) at depth. The amount of heat discharged by surface thermal manifestations or heat discharge rate determines the renewable minimum amount of geothermal resources. Below we provide updated information on heat yield by natural thermal manifestations. The most intense heat yield is associated with the functioning of active hydrothermal systems as various forms of hydrothermal activity concentrate on a small area on the surface. In Kamchatka, the largest modern hydrothermal systems and thermal manifestations are located in the East Kamchatka and Central Kamchatka volcanic belts.

The analyzed data on the assessment of the forecast geothermal resources of hydrothermal systems and fields can be used as a necessary material for the preliminary selection of specific objects during exploration work, the results of which are concerning Kamchatka's explored geothermal fields. It is noteworthy that the increasing use of geothermal resources to generate electricity and heat energy is associated with the importance of saving fossil fuels, especially in the areas that do not have their own oil and gas reserves. In addition, the use of geothermal plants to produce energy minimally pollutes the environment, especially when it is possible to re-inject waste water and steam condensate into geothermal reservoirs.

2. HEAT DISCHARGE OF HYDROTHERMAL SYSTEMS

The amount of heat discharged by surface thermal manifestations or heat discharge rates determines the minimum renewable amount of geothermal resources. All known large hydrothermal systems and thermal manifestations are located in the East Kamchatka and Central Kamchatka volcanic belts. About 150 groups of thermal springs, characterized by different temperatures and chemical composition of water, including 11 high-temperature hydrothermal systems, have been united by Yu.F. Manukhin and V.M. Sugrobov in four geothermal provinces (Vorozheykina et al, 1980) (Fig. 1). Their classification is based on common geological, structural and hydrogeological conditions.

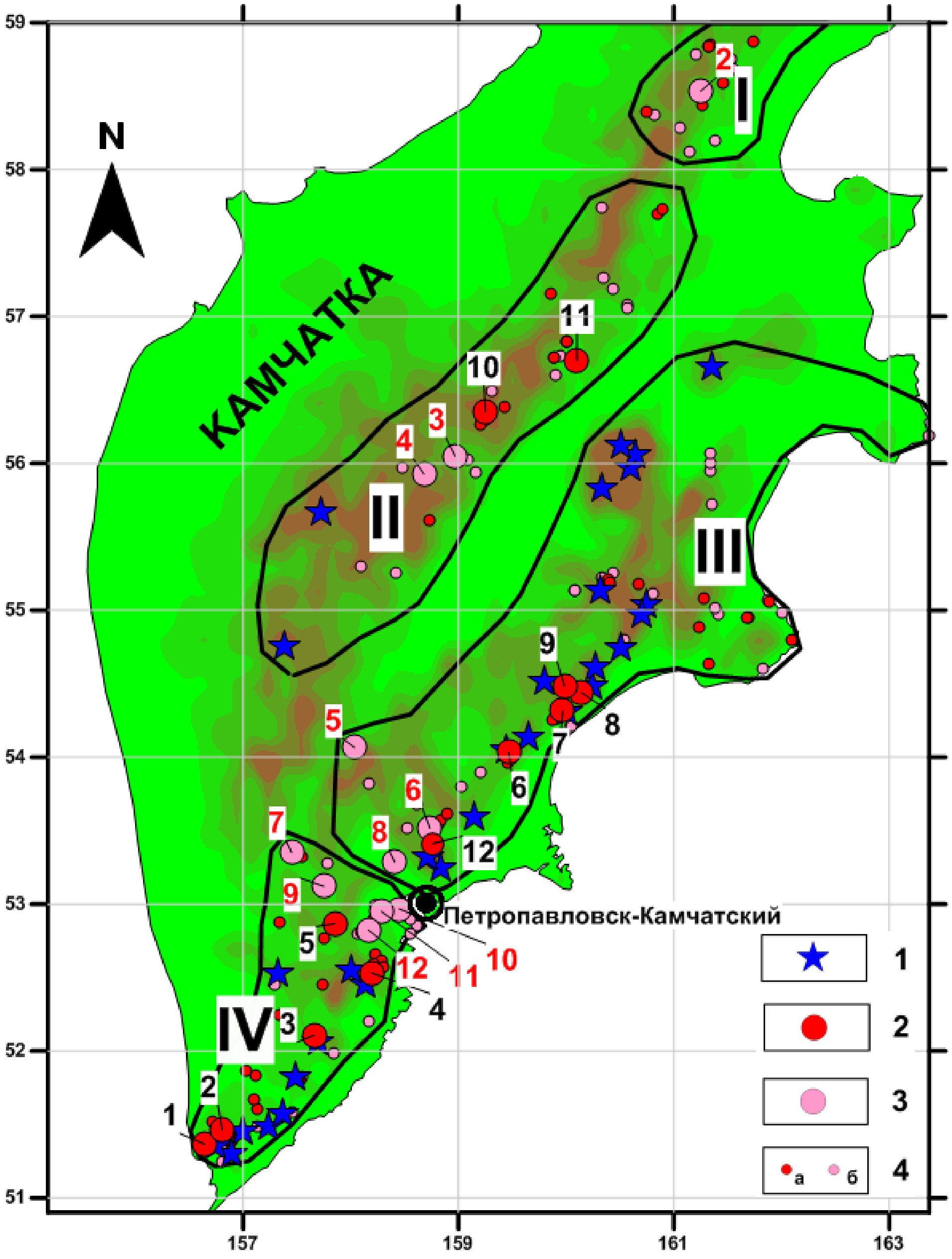

Figure 1: Location of the main groups of Kamchatka's hot springs and hydrothermal systems, - geothermal provinces: I – North Kamchatka, II - Central Kamchatka, III - East Kamchatka, IV - South Kamchatka. Legend: 1 – active volcanoes; 2- high-temperature hydrothermal systems (1- Koshelevsky, 2- Pauzhetsky, 3- Khodutkinsky, 4- Mutnovsky, 5- BolsheBanny, 6- Karymsky, 7 - Semyachik, 8- Geyzerny, 9- Uugnsky, 10- Apapelsky, 11- Kireunsky, 12- North-Koryaksky), see Tables 1 and 2; 3 –Low temperature hydrothermal systems (2 – Ruskovsky, 3 – Anavgaisky, 4 – Essovsky, 5 – Pushinsky, 6 – Nalychevsky, 7 – Malkinsky, 8 – Pinachevsky, 9 – Nachikinsky, 10 – Yuzhno-Berezhny, 11 – Paratunsky, 12 – Verkhne-Paratunsky), see Table 3; 4 – groups of thermal springs and their temperature: a - 50-100°C, b - 20-50°C. Axes units are degrees of east longitude and north latitude.

The assessment of heat yield by surface thermal manifestations was made with regard to four geothermal provinces confined to volcanic belts (Table 1). The natural thermal discharge capacity of hydrothermal systems is determined by the amount of heat discharged by each type of thermal manifestation, including latent heat discharge into surface ponds, heat transfer from the surface of heated soil and thermal reservoirs, conductive heat loss through an impermeable top overlying the geothermal reservoir. Heat discharge was calculated relative to the average annual air temperature (about 0°C for Kamchatka conditions).

In the North-Kamchatka geothermal province, 16 groups of thermal springs with different temperatures were identified. The maximum water temperature (75-95°C) was recorded in the Palansky and Rusakovsky springs.

In the Middle Kamchatka geothermal province there are 26 groups of thermal springs, including two groups of boiling sources (Kireunsky, Apapelsky).

In the East-Kamchatka geothermal province there are 52 groups of thermal springs, most of which are located in the East-Kamchatka volcanic belt. Among them there are boiling springs and steam jets of surface manifestations of large hydrothermal systems: Uzon, Geyserny, Semyachinsky, each of which has a thermal capacity of 268 MWt, 321 MWt, 314 MWt, respectively.

In the South Kamchatka geothermal province, there are 55 various thermal manifestations, including those associated with high-temperature hydrothermal systems: Mutnovsky, Bolshe-Banny, Pauzhetsky, Koshelevsky. Hydrothermal systems of the South Kamchatka province are most studied with the help of boreholes, and geothermal fields identified on the basis of exploration ensure the use of geothermal resources and GeoPP operation. Primarily, these are the Pauzhetsky and Mutnovsky fields. On the basis of this former, the Pauzhetsky GeoPP has been operating since 1967, the installed capacity of which is now 11 MWe. Verkhne-Mutnovsky and Mutnovsky GeoPP with the installed capacity of 12 and 50 MWe respectively, operate at the two sites of the Mutnovsky field. Exploration drilling was carried out at two other fields within the high-temperature systems: Bolshe-Banny and Nizhne-Koshelevsky.

The geothermal resources of thermal water basins, which are formed under the influence of regional heat flow beyond the development of modern surface thermal manifestations, are little studied. The areas of their formation belong to a separate geothermal province of major structural depressions. It combines the West Kamchatka Trough, the Central Kamchatka Trough, the East Kamchatka Trough and other smaller structures (Kononov and Sugrobov, 1997).

Table 1 Heat discharge by Kamchatka hydrothermal systems

Thermal springs, hydrothermal systems	**Heat discharge, MWh**							
	Geothermal provences				**Volcanic belts**			**Total in Kamchatka**
	I	**II**	**III**	**IV**	**Central Kamchatsky**	**East Kamchatsky**	**Belts in total**	
Thermal springs with temperatures up to 100°C	**81.3**	**21.8**	**198.3**	**230.8**	**288.8**	**114.5**	**403.3**	**532.2**
High temperature hydrothermal systems	**-**	**40.5**	**1049.0**	**692.2**	**119.5**	**1662.2**	**1781.7**	**1781.7**
Total	**81.3**	**62.3**	**1247.3**	**923.0**	**408.3**	**1776.7**	**2186.0**	**2313.9**

3. IDENTIFIED GEOTHERMAL RESOURCES OF THE HIGH TEMPERATURE HYDROTHERMAL SYSTEMS

The calculation of the estimated useful geothermal resources was carried out in two general ways: (1) by the amount of heat discharged by natural thermal manifestations in the area of systems and fields (heat discharge capacity); (2) according to the determination of the reservoir's thermal energy contained in rocks saturated with fluid and distributed within hydrothermal systems.

3.1 Estimates of the Indentified Geothermal Resources by Using Natural Heat Discharge Data

The approach to such an assessment is based on the assumption that the thermal discharge rate, determined by the amount of heat discharged by natural surface thermal manifestations, is identified with minimal geothermal resources, which may be increased at the penetrating of deep horizons by wells in the process of field exploration and exploitation. The order of such an increase (increase factor) is determined by comparing the heat discharge from explored geothermal fields obtained from production wells and estimates of the natural thermal discharge rate of hydrotherms. For example, for the Pauzhetsky field, heat discharge from production wells of the explored site is almost three times the value of hydrotherm natural discharge, with a stable production and a constant temperature and pressure in the wells (Sugrobov, 1976). With heat discharged by natural thermal manifestations of the Pauzhetsky geothermal field of 63 MW, the heat extracted by wells with a stable mode in the field's Northern section amounted to 146 MW and with a thermal power of the entire system of 104 MW, the total heat extraction by geothermal wells at the field could reach 350 MW. An even more significant increase in reserves was noted at the Bolshebanny field. The data on world known geothermal fields (Wairakei - New Zealand; Larderello - Italy; California geysers - USA, etc.) also indicate that the heat production by wells exceeds the heat discharge by natural thermal manifestations several times. For example, in Wairakei, about 2,300 MW are taken from wells, thermal discharge capacity is 418 MW.

In this connection, the data are indicative on the ratio of heat production by wells and the initial thermal discharge rate during long-term operation of the Pauzhetsky and Mutnovsky geothermal fields. Heat extraction during a long-term operation of the Pauzhetsky field (Kiryukhin et al, 2004, 2008) and during a perennial operation of the Mutnovsky field (Kiryukhin et al, 2018) exceeds the initial natural discharge by 3-4 and 6-7 times, respectively, that is, the magnification value is close to its definition according to the initial period of field exploitation. Therefore we may assume that the quantitative ratios of the predicted heat production rate at geothermal fields and heat dicharge by natural thermal manifestations are not accidental and allow us to assess the possible energy potential of Kamchatka's high-temperature geothermal fields.

Estimation of identified geothermal resources for Kamchatka fields, confined to high-temperature hydrothermal systems, was performed using an increase factor of thermal discharge power equal to 4 and 7 and a coefficient of transfer to thermal energy to useful work at the wellhead 0.23. Taking this into account, the estimated geothermal resources of high-temperature hydrothermal systems, excluding Geysernaya, Semyachik and Uzon, located in the Kronotsky Reserve, amount to about 1,700 MW of heat (Table 2).

3.2 Estimates of Identified Geothermal Resources by Using Heat Energy Stored in Geothermal Reservoirs

This approach, substantiated in the works (Muffler and Cataldi, 1978), is based on the determination of thermal energy contained in rocks saturated with fluid and distributed within hydrothermal systems. The thermal energy of a reservoir is calculated from the volume of a block, layer or reservoir of heated rocks, the specific heat content of rocks and their temperature. A centenary operation of geothermal reservoirs is expected.

When determining the volume of the reservoir, its vertical thickness for all systems is assumed to be the same (2.5 km), based on the top at a depth of 0.5 km and the base depth of the system - 3 km. The volume of reservoirs is estimated by the size of the area, determined by the distribution of surface thermal manifestations, features of the site's geological structure and hydrogeological conditions.

The temperature in the depths of the systems, estimated by chemical geothermometers, calculations based on heat flow measurements or measurements in wells, varied from 150 to 220°C for hot water systems and from 200 to 310°C for steam dominant systems. However, the temperature distribution in specific reservoirs for most systems is still unknown, since exploratory drilling has not been carried out. Therefore, for approximate calculations of thermal energy in the reservoir, the temperature was assumed to be average, the same, for all hot water systems — 200°C and steam dominated systems — 220°C.

The specific heat capacity of rocks saturated with water and steam and represented mainly by volcanic rocks and volcanogenic-sedimentary rocks, was assumed to be 2.7 J / cm^3°C , as in (Muffler, 1979). The thermal energy of the reservoir (q_R) is determined by the formula $q_R = VC\ (T-T_1)$, where T is the average temperature (°C) in the system's interior in a layer of 0.5–3.0 km, T_1 is the average annual air temperature (for Kamchatka, about 0° C degrees C), C is the specific heat capacity of rocks saturated with fluid (2.7 J / cm^3°C). Using the ratio of the reservoir's heat energy to the useful work of 0.057 and 0.061 (Muffler, 1979, Fig. 5 p.26), respectively, for reservoirs with an average temperature of 200 and 220°C, identified geothermal resources are calculated, the values of which for specific fields are given in Table 2. Their total value (about 2800 MW of heat) has the same order as the resources determined by heat discharge by natural thermal manifestations (1710 MW). These estimates should be oriented when setting up exploratory or production drilling.

The obtained values of the identified geothermal resources are approximately equivalent to 1120 MWe and 680 MWe of electric power, respectively. An accurate estimate of the amount of electrical power is determined by the characteristics and efficiency of the power plants used.

Table 2 Identified geothermal resources of Kamchatka’s high temperature hydrothermal systems

# in Figure 1	Hydrothermal systems and fields	Phase conditions	Natural heat discharge rate MWh	Area, km^2	Volume of reservois, km^3	Average temperature (maximum in wells) °C	Heat capacity of reservoir10^{18} J	Identified geothermal resources, MWh	
								Based on heat content estimates	Based on heat discharge estimates
1	Koshelevsky	Steam	314[1]	15±4,5	37,5±11,2	220	22,27±6,7	431±129	505,5
	Nizhne-Koshevsky		104[1]	7±2,1	17,5±5,2	220 (240)*	10,39±3,11	201±60	
2	Pauzhetsky	Two-phase	104[2]	18±5,4	45±13,5	200 (220)*	25,78±7,73	466±140	95,7
	Pauzhetsky		62.8[2]	7±2,1	17,5±5,2	200(218)*	9,45±2,83	171±51	
3	Hodutkinsky	Water	42[3]	12,0±3,6	30±9	200	16,2±4,8	293±88	29
4	Mutnovsky	Steam, two-phase	546[4]	32±9,6	80±24	220	47,52±14,2	920±276	879
	North-Mutnovsky		129[4]	12±3,6	30±9	220(301)*	17,82±5,3	345±103	
5	Bolshe-Banny	Two-phase	79[5]	6±1,8	15±4,5	200(171)*	8,1±2,43	147±44	72,7
6	Karymsky		146[6]	15±4,5	37,5±11,2	200	20,25±6,1	366±110	100,7
10	Apapelsky		16[7]			200			11
11	Kireunsky		24.5[8]	7±2,1	17,5±5,2	200	9,45±2,83	171±51	16.9
Sum								2794±838[9]	1710,5

Notes: Data of heat discharge from: 1)- E.A. Vakin, 1976; 2)-V.M. Sugrobov, 1976; 3)-T.P. Kirsanova, I.V. Melekestsev, 1984; 4)-E.A. Vakin, 1976a; 5)-Y.A. Kraevoiet al, 1976; 6)-G.F. Pilipenko, 1989; 7)- 8)-T.P. Kirsanova, 1971; 9) – Data from Nizhne-Koshelevsky, Pauzhetsky, North-Mutnovsky geothermal fields are incorporated into characteristics of the corresponding hydrothermal systems.

3.3 Estimate of Electricity Production Power Using its Correlation with the Volcanoes Number

The relationship between volcanic and hydrothermal activity may also be used to predict the electrical performance of hydrothermal systems. Analysis of data for the eight largest geothermal electrical energy producing countries (Iceland, USA, Indonesia, Philippines, Japan, Mexico, New Zealand, Italy (Tuscany)) shows that there is a statistically significant linear correlation between the number of active volcanoes and the predicted geothermal resources providing electrical performance of hydrothermal systems (V. Stefansson, 2005), i.e. one active volcano is capable of forming a hydrothermal system adjacent to it with a predicted electrical power of 158 MW (with an error of ± 13%). Of course, the question of how and where active volcanoes accumulate magma to generate hydrothermal systems adjacent to them remains open.

There are 29 active volcanoes functioning in Kamchatka: Kambalny, Koshelevsky, Dikiy Greben, Ilinsky, Zheltovsky, Ksudach, Khodutka, Opala, Mutnovsky, Gorely, Avachinsky, Koryaksky, Zhupanovsky, Karymsky, M. Semyachik, Townshits, Kikhpinych, Krasheninnikov, Kronotsky, Kizimen, Komarov, Gamchen, Tolbachik, Ushkovsky, Klyuchevskoy, Sheveluch, Bezymyanny, Khangar, Ichinsky. Then the total estimate of the projected electrical performance of adjacent hydrothermal systems will be 29 * 158 = 4582 MWe. Excluding seven volcanoes belonging to the Kronotsky Reserve (Townschitz, Kikhpinych, Krasheninnikov, Kronotsky, Kizimen, Komarov, Gamchen), we obtain the predicted electrical capacity of 22 * 158 = 3476 MWe. Taking into account the above error, the range of the predicted electrical performance of Kamchatka’s high-temperature hydrothermal systems is estimated from 3,024 to 3,927 MWe.

4. IDENTIFED GEOTHERMAL RESOURCES OF THE LOW TEMPERATURE HYDROTHERMAL SYSTEMS

Large geothermal fields with a temperature in the depths of less than 150°C are sites of low-temperature hydrothermal systems. They are associated with numerous thermal springs with a temperature of 20-95°C, Fig.1 shows the location of the main groups. Due to the relatively poor knowledge of low-temperature hydrothermal systems and, probably, their specifics, it is not possible to establish a definite relationship between resources and heat yield by surface thermal manifestations.

Calculation of the estimated resources of low-temperature hydrothermal systems was carried out using thermal energy contained in the reservoir rocks, the volume of which was chosen by analogy with the explored fields, taking into account the distribution of surface thermal manifestations, their power and geological structure according to the scheme offered in (Muffler, 1979). The depth of the reservoirs top was taken to be an average of 0.5 km, and the thickness to be 2.5 km. The average reservoir temperature was determined by geochemical geothermometers and measurements in wells. Uncertainty in estimating the volume of a geothermal reservoir is expressed by an error of at least 30%. Baseline data for the assessment of the identified resources as prospective for direct use with a temperature of less than 150 ° C are given in Table 3. Their estimated resources are over 413 MW (heat). The identified geothermal resources of known fields and 43 hydrothermal systems within four geothermal provinces amount to about 1,350 MW (thermal) with an estimated centenary use.

Table 3. Identified Geothermal Resources of the Kamchatka Low Temperature Hydrothermal Systems

Geothermal field	Max. Temperature of the springs,°C	Natural heat discharge, MWh	Area, км^2	Volume, km^3	Estimated temperature, °C	Heat energy stored, 10^{18} J	Identified geothermal resources MWh	Notes
Tymlatskoe	47..5	5.0	2. 5 ± 0.7	3.7 ± 1.1	115	1.1.5 ± 0.34	20.8 ± 6.2	
Palanskoe	95.0	7.5	6.5 ± 2.0	9.7 ± 2.9	105	2.75 ± 0.8	49.75 ±14.9	Springs with a temperature from 30°C to 95°C
Rusakovsky	76.5	57.8	10.0 ±3.0	15.0 ± 4.5	90	3.64 ± 1.1	65.8 ± 19.7	Several groups of springs with a temperature from 36°C to 76,5°C
Anavgaisky	52.0	7.4	1.5 ± 0.4	2.2 ± 0.7	115	0.68 ± 0.2	12.3 ± 3.68	Heat supply of Anavgai village and green houses
Essovsky	65.0	4.4	3.0 ± 0.9	4.5 ± 1.3	104	1.26 ± 0.38	22.8 ± 6.8	Heat supply of Esso village and green houses
Pushinsky	46.0	1.5	2.5^0.7	3“7^1.1	110	1.1 ± 0.33	19.9 ± 5.9	Exploration drilling done
Nalychevsky	75.0	9.4	11.0 ± 3.3	16.5 ± 4.9	143*	6.37 ± 1.9	11..5 ±3.4	
Malkinsky	83.0	9.4	2.5 ± 0.7	3.7 ± 1.1	128*	1.28 ± 0.33	23.2 ± 6.97	Exploration drilling done
Pinachevsky	12.5	0.8	1.50 ± 0.4	2.2 ± 0.7	95	0.56 ± 0.17	10.1 ± 3.03	One exploration well penetrated 53.5°C.
Nachikinsky	81.0	4.2	1.5 ± 0.4	2.2 ± 0.7	106*	0.63 ± 0.19	11.4 ± 3.4	Exploration drilling done
Yuzhno-Berezhny	20.0	0.2	2.0 ± 0.6	3.0 ± 0.9	90	0.73 ± 0.22	13.2 ± 3.95	Exploration drilling done
Paratunsky	81.5	8.2	10.0 ± 3.0	15.0 ± 4..5	110	4.46 ± 1.34	80.6 ± 24.2	Heat supply of Paratunsky and Thermalny villages and green houses
Verkhne-Paratunsky	70.5	20.6	9.0 ± 2.7	13.5 ± 4.0	110	4.01 ± 1.2	72.5 ±21.7	Exploration drilling done

Notes: * - from Barabanov et al, 1979.

5. SHALLOW MAGMA CHAMBERS OR ENHANCED GEOTHERMAL SYSTEMS-2 (EGS-2)

Currently, the quantitative calculation of their resources is rather conditional due to poor knowledge of the problem of extracting heat accumulated by melted rocks. An estimate of the amount of heat in the Avachinsky volcano magma chamber is given in (Fedotov et al., 2007). For elliptical approximation, its shape (Fedotov and others) is as follows: for a small ellipsoid (with semi-axes of 1.53 and 2.3 km) with a decrease in temperature from 900 to 150°C - $0{,}7\cdot10^{20}$ J, for a large ellipsoid (with semiaxes 3 and 4.5 km) with a decrease in temperature from 700 to 150°C is $4{,}1\cdot10^{20}$ J. It is assumed that shallow magmatic chambers have the volcanoes Koshelevsky, Khodutka, Opala, Ipelka, Gorely, Mutnovsky, Dzenzur, Kizimen and others, and the Ksudach caldera. When calculating the heat resources of other volcanoes, the volumes of magma chambers were assumed to be 10 km^3, with the exception of the Tolbachik Volcano volcanic rift (30 km^3). The minimum amount of geothermal resources of Kamchatka's magma chambers is estimated at n x 10^{21} J.

Further research on the formation of hydrothermal systems adjacent to active volcanoes led to the following results. Analysis of local seismicity within the Avachinsky-Koryaksky volcano group in the period 2000-2016 allows to identify a sequence of plane-oriented clusters of earthquakes, interpreted as a process of introducing dikes and sills (Kiryukhin et al., 2017). Magma injections are identified in the following zones: (1) a shallow crust magmatic chamber in the Koryaksky volcano southwestern part consisting of a combination of dikes and sills in the depth range from -2 to -5 km abs .; (2) the zone of dike accumulation in the submeridional zone (7.5 x 2.5 km) in the depth range from -2 to -5 km abs .; (3) a shallow magmatic chamber in the Avachinsky volcano cone in the range of marks from 1 to 2 km abs.

Conceptual TOUGH2 modeling has been used to understand and explain the mechanism of formation of the hydrothermal system under the Koryaksky volcano (Kiryukhin et al, 2017). In this regard, the following model parameters turned out to be the most important: (1) sources of heat generation 20 MW / km^3 and gas generation (CO_2) 10 g / s / km^3, operating for 7000 years in the above-mentioned magma injection zones; (2) water supply at a rate of 580 kg / s through the volcano vents to the dike injection zones. The simulation results are consistent with estimates of Na-K geothermometers (300 ^{o}C), data on water isotopic composition (δD, δ18O), indicating a high position of the water supply area, magmatic CO_2 concentration (up to 4 g / kg) in thermal mineral springs on the Koryaksky volcano northern slope, thermal effects during dike injection dated 02.08.2011, registered at the Izotovsky thermal mineral source and the original seawater dilution in the Koryaksky volcano basement as a result of the downward circulation of cold waters. The simulation also shows the possibility of a hidden high-temperature reservoir under the Koryaksky volcano southern slope (at elevations from −1 km abs.), which may be the goal of the subsequent exploratory drilling.

Analysis of local seismicity within the Klyuchevskaya volcano group and Shiveluch volcano in the period 2000–2017 allows to identify a sequence of plane-oriented clusters of earthquakes, interpreted as a process of introducing dikes and sills (magmatic fracking) (Kiryukhin et al., 2018). The geometry of magmatic bodies reflects the geomechanical conditions in volcanic bodies and foundations. The magma fracking within active volcanic structures leads to the formation of permeable reservoirs with a vertical length of up to 35 km (Klyuchevsky) and a diameter of up to 15 km (Shiveluch) depending on the geomechanical state of the host rocks. These reservoirs are objects of subsequent hydrothermal circulation with the possibility of the formation of geothermal, ore and oil and gas fields. To assess the formation conditions of hydrothermal reservoirs, TOUGH2-EOS1sc modeling is used in the temperature range of up to

1200°C and pressures up to 1000 bar. We demonstrate the possibility of forming high-temperature hydrothermal reservoirs under active volcanoes due to deep circulation (up to depths of -35 km abs) with a discharge of 12 to 106 kg / s (from 20 to 140 MWt) and the formation of near-surface high-temperature (220–300°C) geothermal fields. (top at elevations from 0 to –1.5 km abs.).

6. UNITED NATIONS FRAMEWORK CLASSIFICATION FOR GEOTHERMAL RESOURCES (UNFC).

In recent years, attempts have been made to develop a unified classification of energy resources (oil, gas, geothermal energy) (United Nations Framework Classification for Resources (UNFC)). In this classification, there are three categories of assessment. E - economic feasibility, F - technical feasibility, G - geological knowledge. Each of these categories has three main grades, the unit of measure of the resource is Petajoule (electric or thermal). Petajoule is 10^{15} joules. An example of UNFC use for the Pauzhetsky geothermal field can be found in Case Study 12 section: Pauzhetsky geothermal field Application of the United Nations Framework Classification for Resources (UNFC) concerning geothermal energy resources, 2017, 96 p. at:

https://www.unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/UNFC_GEOTH/1734615_E_ECE_ENERGY_110_WEB.pdf

7. GEOLOGICAL CONDITIONS, CURRENT STATUS AND NEAR FUTURE POSSIBILITIES OF GEOTHERMAL DEVELOPMENT IN KAMCHATKA, RUSSIA

7.1 High Temperature Geothermal Field Mutnovsky

The Mutnovsky geothermal area is part of the Eastern Kamchatka active volcano belt. Mutnovsky, 80 kY old and an aging strato-volcano (a complex of 4 composite volcanic cones), acts as a magma- and water-injector into the 25-km-long North Mutnovsky extension zone (Fig. 2, Kiryukhin et al, 2018). Magmatic injection events occurring in the NE sector of the volcano (2× 10 km2) at elevations from −4 to −2 km, while some magmatic injections occur at elevations from −6.0 to −4.0 km below the Mutnovsky production field. Water recharge of production reservoirs is from the Mutnovsky volcano crater glacier (+1500 to +1800 masl), which was confirmed by water isotopic data (δD, δ18O) of production wells at an earlier stage of development. The Mutnovsky (Dachny) 260–310 °C high-temperature production geothermal reservoir with a volume of 16 km^3 is at the junction of NNE- and NE-striking normal faults, which coincides with the current dominant dyke injection orientation. Modeling was used to reproduce the history of the Mutnovsky (Dachny) reservoir exploitation since 1983 with an effective power of 48 MWe by 2016. Modeling also showed that the reservoir is capable of yielding 65–83 MWe of sustainable production until 2055, if additional production drilling in the SE part of the field is performed. Moreover, this power value may increase to 87–105 MWe if binary technologies are applied.

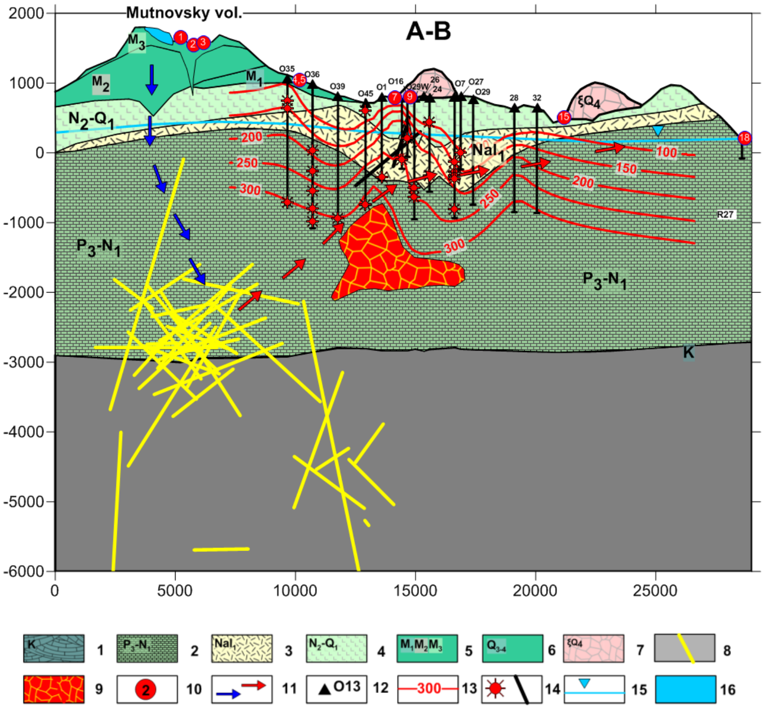

Figure 2: Geological cross-section (from south to north) (Kiryukhin et al, 2018). Legend: 1 – Cretaceous basement; 2 – Miocene sandstones and Tertiary volcano-sedimentary deposits; 3 – Miocene dacite and rhyolite tuffs and lavas; 4 – Pliocene-Quaternary basalts and andesite tuffs and lavas; 5 – Mutnovsky 1, 2 and 3 volcanic cones, respectively; 6 – Upper Pleistocene and Holocene andesites and basalts; 7 - Upper Pleistocene and Holocene rhyolite extrusions; 8 – Magmatic injection (dykes) 2009-2016 traces; 9 – Diorite intrusion (zone of previous dyke emplacements); 10 - thermal features (referenced in text and Fig. 1); 11 – assumed fluid flows (cold – blue, thermal – red); 12 – wells with corresponding numbers; 13 – isotherms, °C; 14 – Production feed-zones and 2D plane production zone traces; 15 – geothermal

production reservoir water level; and 16 - Mutnovsky volcano glacier. Axes scale numbers are given in meters, vertical exaggeration is 2.5.

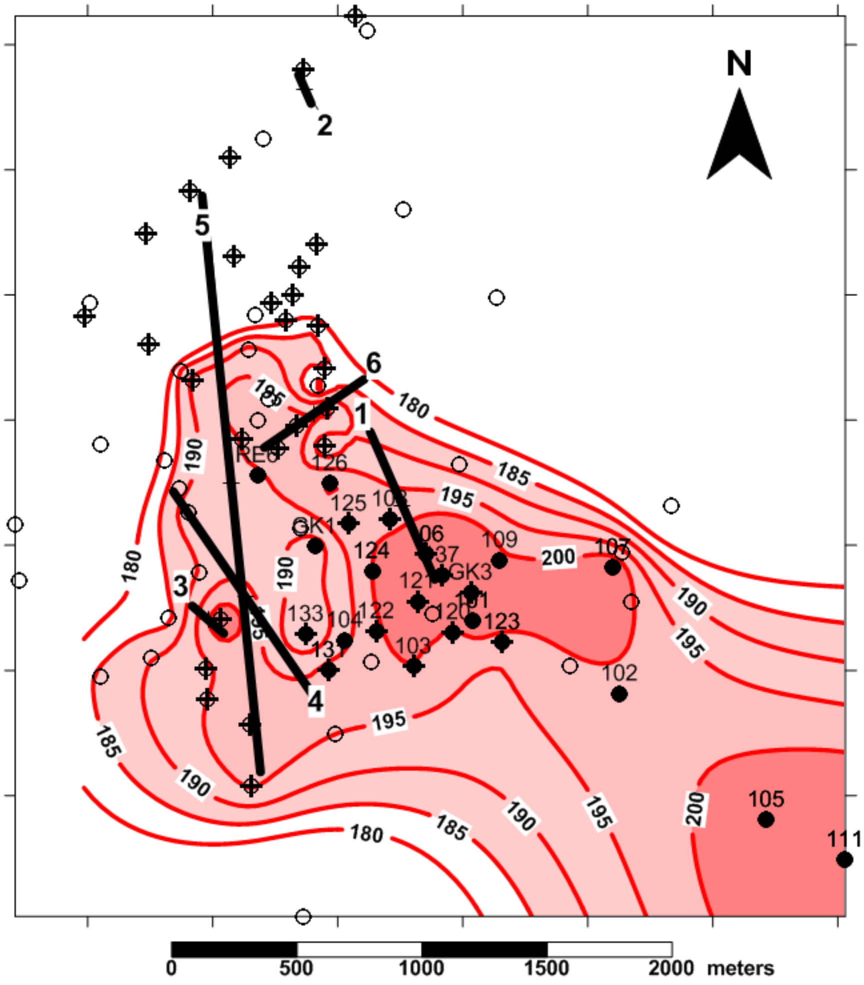

Figure 3: Structural control on the Pauzhetsky production reservoir (Kiryukhin et al, 2004). Temperature counters in production geothermal reservoir are averaged in the depth range from -500 to 0 masl. Wells that penetrated dacite extrusion Q_{2-3} are marked by black circles, production wells and reinjection wells with high productivity marked with crosses. Production faults traces at -350 masl are shown by black thick lines and marked with faults numbers. Scale axis is 500 m.

7.2 High Temperature Geothermal Field Pauzhetsky

A three-dimensional numerical model of the Pauzhetsky geothermal field has been developed based on a conceptual hydrogeological model of the system (Kiryukhin et al, 2004, 2008). It extends over a 13.6-km^2 area and includes three layers: (1) a base layer with inflow; (2) a geothermal reservoir (Fig. 3); and (3) an upper layer with discharge and recharge/infiltration areas. Using the computer program iTOUGH2 (Finsterle, 2004), the model is calibrated, combining natural-state and 1960–2006 exploitation data. Heat and mass balances derived from the model were used to identify the sources for the geothermal reserves in the field. By November 2005, the mass balance for the geothermal reservoir showed that the fluids being produced were contributed by the base-layer upflow (25.7%), meteoric inflow through hydraulic windows (30%), reservoir-fluid storage (fractures 15.3%, matrix 20.7%), and injection (8.3%). Similarly, heat balance indicated the following thermal contributions: base layer convective heat upflow (30.8%), reservoir heat storage (fractures 25%, matrix 38.3%), injection (5.1%), and meteoric water inflow (0.8%).With the addition of five makeup wells, simulation forecasts for the 2007–2032 period predict a sustainable average steam production of 29 kg/s, which is sufficient to maintain the generation of 6.8 MWe at the Pauzhetsky power plant.

Significant breakthrough up to 40 MWe is possible in Pauzhetsky, if binary technology with full reinjection, high flow rate circulation and shaft downhole pumps is used (study is underway). Bolshe-Banny is the analog of the Pauzhetsky and may produce comparable electricity, as well as geothermal heat energy from adjacent geothermal fields.

7.3 Low Temperature Geothermal Field Paratunsky

The Paratunsky low temperature geothermal field has been operating since 1964 (Figs. 4 and 5). During the exploitation period from 1966 to 2014, 321 Mt of thermal water with temperatures of 70–100°C was extracted and used for district heating, balneology and greenhouses. Water isotope data analysis indicated that the main recharge region of the Paratunsky geothermal reservoirs is the Viluychinsky Volcano (2173 masl) and the adjacent highly elevated structures, located 25 km south from the geothermal field. Production zones coinciding with dip angle fractures occur in the condition of radial extension (possibly caused by magmatic origin heat sources below the reservoir) and hydraulic fracturing (possibly caused by the elevated position of the Vilyuchinsky Volcano's recharge region). A 3D numerical thermal-hydrodynamic model of the Paratunsky geothermal reservoir (Kiryukhin et al., 2017) was applied to demonstrate the possibility of achieving a flowrate of 1375 kg/s for 25 years , using submersible pumps installed at 210 m below earth surface. Preliminary analysis of economic feasibility shows that the payback of the project is 4.8 years with existing prices for heat energy, discounting and inflation rates. Annual heat energy production is expected to be 1630 thousand Gcal (216 MWt), that will cover the energy demands of the central heating systems of Petropavlovsk-Kamchatsky. If the Verkhne-Paratunsky geothermal reservoir (which is an analog of the Paratunsky reservoir with comparable capacity) is included, this will completely cover all heat energy needs of the main Kamchatka consumers.

9. CONCLUSIONS

The development of Kamchatka's geothermal resources use is possible in two main applications: generation of electrical energy at high-temperature geothermal fields and heat supply through the use of low-temperature geothermal fields. Currently, the installed electrical capacity of Mutnovsky GeoPP is 62 MWe. (at actual output of about 50 MWe.), the installed capacity of the Pauzhetsky GeoPP is 12 MWe. (at real output from 4 to 5 MWe). The Paratunsky geothermal field is used for local heat supply with a mass flow rate of 254 kg / s (heat extraction 53 MW with a weighted average temperature of production wells of 80°C and utilization temperature of 30°C).

Kamchatka's identified geothermal resources are estimated to be sufficient for generating electricity with a capacity from 680 to 1100 MWe (by the volumetric method and by natural thermal discharge) and from 3000 to 3900 MWe (by the intensity of volcanic activity). The identified geothermal resources for heat supply are estimated at about 1350 MW (thermal).

The use of numerical thermo-hydrodynamic TOUGH2-modeling with a forecast of exploitation of productive geothermal reservoirs with a known reservoir and energy properties shows: (1) The possibility of increasing the electrical productivity of already exploited areas of the Mutnovsky geothermal field up to 105 MWe, the Pauzhetsky geothermal field to 11 MWe, including the use of binary technologies; (2) The possibility of increasing heat generation during the operation of the Paratunsky geothermal field with submersible pumps up to 216 MWh, which ensures heat consumption in the Petropavlovsk-Kamchatsky centralized heat supply systems.

Further prospects for increasing geothermal electricity and heat supply in Kamchatka may also be associated with the exploration of partially explored Bolshe-Banny, Nizhne-Koshelevsky and Verkhne-Paratunsky geothermal fields. The use of geothermal resources of the latter for energy purposes in combination with the increase in capacity of the Mutnovsky GeoPP and the Pauzhetsky GeoPP solves the problem of reliable and complete power supply to the south and center of the Kamchatka region at the expense of geothermal energy sources.

The use of detailed seismological observations in combination with thermo-hydrodynamic TOUGH2-eos1sc modeling at accessible depths for drilling revealed hidden geothermal reservoirs with hydrothermal circulation, associated with the magmatic feeding systems of Mutnovsky and Koryaksky volcanoes. These reservoirs may also be considered as targets for exploratory drilling for geothermal energy.

This study was carried out with the support of the RFBR for the project 18-05-00052-19.

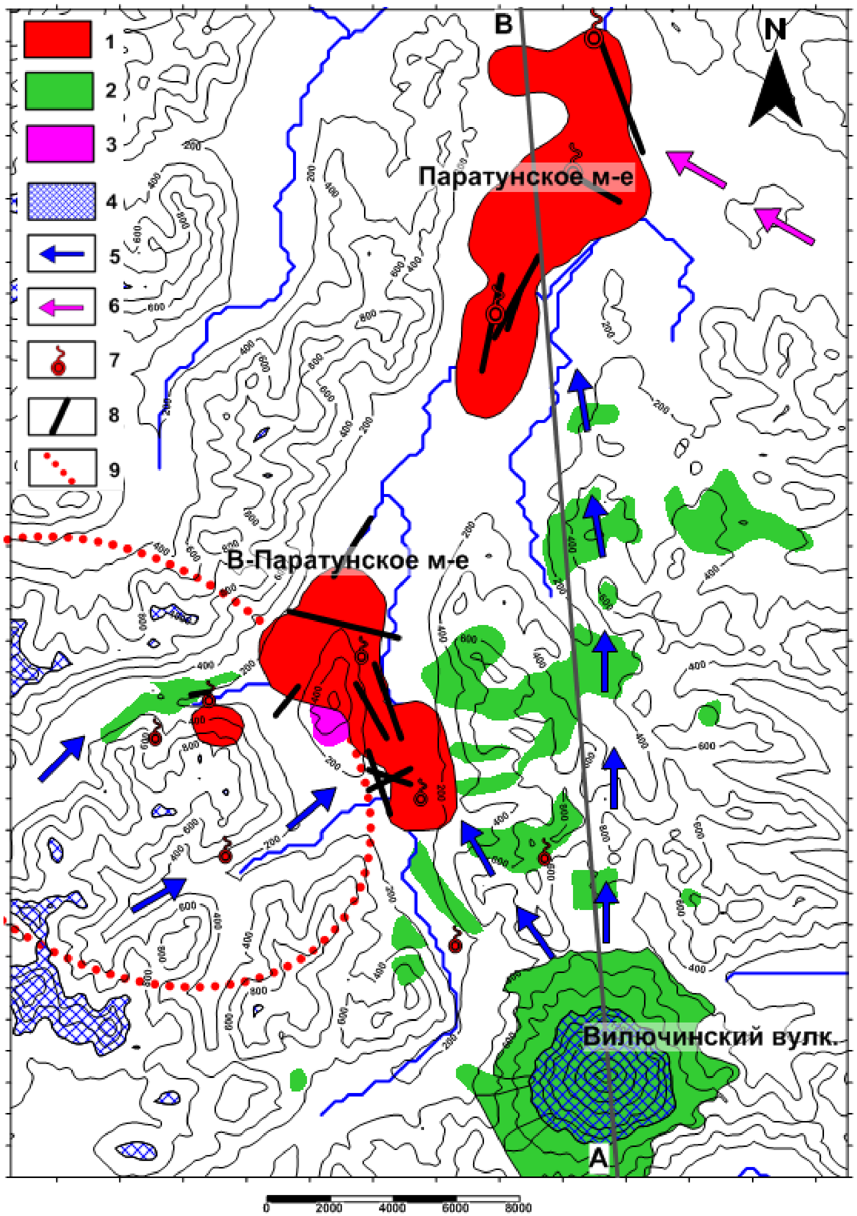

Figure 4: Model of the Paratunsky geothermal fields geo-filtration structure, recharge and boundary conditions, topographical elevations in the background, grid scale 2000 m (Kiryukhin et al, 2017). Legend: 1 – counters of production geothermal reservoirs at -750 masl based on geoisotherm 75°C (Paratunsky) and 60°C (Verkhne-Paratunsky); 2 – Holocene lava flows and cinder cones; 3 – Rhyolite extrusions 0.5-0.8 MY; 4 – water recharge regions for the Paratunsky geothermal reservoirs (with an elevation of more than 1000 masl); 5- Horizontal projections of fluid flows from recharge regions to the production geothermal reservoirs; 6 – Chloride water attracted into the production reservoir due to its exploitation; 7 – Hot springs; 8 – Production zone traces at -750 masl; 9 – Leonov caldera rim 1.2-1.5 MY. Bar scale in meters. AB – location line of cross-section, shown in Fig.5.

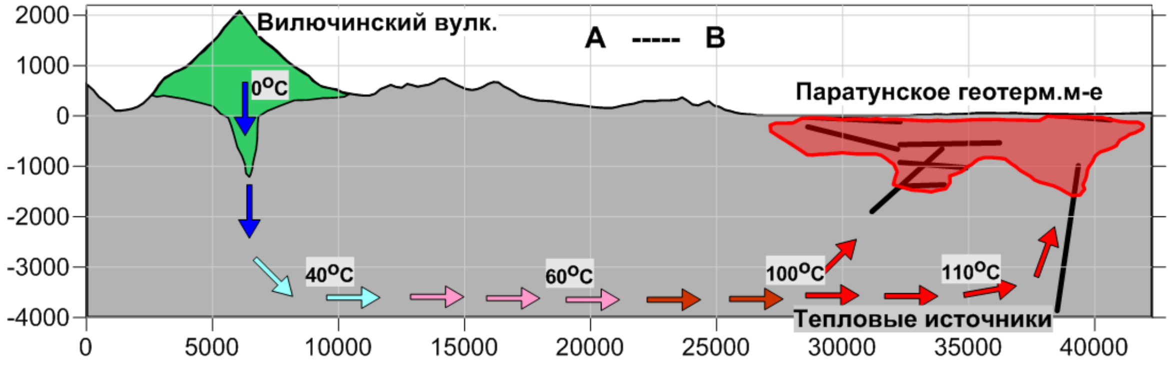

Figure 5: Model of the Paratunsky geothermal field geo-filtration structure, recharge and boundary conditions in a cross section AB, shown in Fig. 4. Axes scale in meters, vertical exaggeration 2.5.

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