

Temperature and Permeability Structure of Low Enthalpy Geothermal Field, Paratunsky, Kamchatka

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ABSTRACT

The Kamchatka Peninsula has the world's highest density of andesitic volcanoes. It also has both high- and low-temperature geothermal systems that are assumed to be powered by subduction-related magmatism. Although high-enthalpy hydrothermal circulation is at time observed close to the surface, we believe that extensive low-enthalpy systems may overlie and receive thermal input from higher temperature systems. Our hypothesis is that the thermal regimes are stacked:

- Magmatic hydrothermal represented by magmas and steep temperature and physical gradients including the brittle-ductile transition and supercritical fluids that have been demonstrated in the Iceland Deep Drilling program. Magmatic fluids may represent a large component of the fluids present.

- High-enthalpy hydrothermal circulation systems that are present in fracture systems overlying the magmatic environment. Fluids are typical NaCl brines as represented by the Mutnovsky geothermal field. Fracture permeability is related to tectonic as well as magmatic processes.

- Low-enthalpy geothermal systems ($T < 150^\circ \text{C}$ at less than 1 Km depth) that are present as both fracture and stratigraphic permeability and are represented by the Paratunsky geothermal field.

1. INTRODUCTION

The Kamchatka Peninsula has the world's highest density of andesitic volcanoes that suggest on-going high-level magmatic activity. The area also has both high- and low-temperature geothermal systems that are assumed to be powered by the subduction-related magmatism. Although high-temperature hydrothermal circulation is at times observed close to the surface (Mutnovsky Geothermal System), we believe that extensive low-enthalpy systems (such as the Paratunsky Geothermal System) may overlie and receive thermal input from higher temperature systems. The current conceptual model of low temperature geothermal systems assumes deep circulation of meteoric water, originating in highlands of a recharge region, mining heat from deep fracture/dykes roots, and then ascending in the form of hot springs discharge in a lowland (Bodvarsson, 1983).

Our hypothesis is that the thermal regimes are stacked:

- Magmatic hydrothermal systems are represented by magmas and steep temperature- and physical-gradients including the brittle-ductile transition (IDDP-1; Elders *et al.*, 2011) and supercritical fluids (IDDP-2; Fridleifsson *et al.*, 2017). This environment has been characterized in ICDP's (International Continental Scientific Drilling Program) Iceland Deep Drilling Program (IDDP). Magmatic fluids may represent a large component of the fluids present.

- High-temperature hydrothermal circulation systems that are present in fracture systems overlying the magmatic environment. Fluids are typical NaCl brines. Fracture permeability is related to tectonic as well as magmatic processes.

- Low-temperature geothermal systems that are present as both fracture and stratigraphic permeability. These may represent cooling of high-temperature systems through conduction or mixing with ground water. ICDP's Hotspot Project has investigated large low-temperature resources in the Snake River Plain, Idaho associated with young volcanic activity and elevated regional heat flow.

Low-temperature geothermal fields, are defined by reservoir temperatures below 150°C at a depth of 1 km (Rybach, 1981; Axelsson and Gunnlaugsson, 2000; Johannesson, 2016). Alternatively, the US Geological Survey (White and Williams, 1975; Muffler, 1978; Reed, 1982) has classified systems as high-temperature ($>150^\circ \text{C}$), intermediate-temperature (150° to 90°C), and low-temperature ($<90^\circ \text{C}$). Importantly, in their assessment of systems in the US, the USGS shows that the number of hydrothermal convective systems increases exponentially with decreasing temperature (Reed, 1982). Although there are many more low-temperature than high-temperature systems, scientific investigations have focused on high-temperature, and there have been few comprehensive studies of low-temperature systems, and few investigations have analyzed the relationship between high- and low-temperature systems. This project will address low-temperature geothermal systems on the Kamchatka Peninsula in particular but in active volcanic environments in general. It therefore complements the success of both the IDDP and Hotspot projects.

Low-temperature geothermal systems have experienced decades of industrial utilization in Iceland, Hungary, China, Turkey, France, Germany, Russia, USA and other countries. This has yielded experience for inferring the fundamental processes present in these fields, including heat and water recharge conditions in the natural state and under exploitation, reservoir properties and renewable energy estimates

Iceland, for example, shows that it is possible to heat the capital city of Reykjavik and neighboring communities (160,000 inhabitants) with 11 PJ/year (Axelsson et al., 2000) using just three low temperature geothermal reservoirs (Reykir, Ellidaar and Laugarnes). Note, that by 2016, the Reykjavik heating system added a total of 450 MWth from Nesjavellir and Hellysheidi high temperature geothermal fields (Johannesson et al., 2016).

The dominant meteoric origin of the Icelandic low temperature geothermal systems was inferred from water isotope studies (Arnason, 1976). Thorough analysis of the long-term exploitation of the nine Iceland low temperature geothermal fields, which are mostly operated under downhole pumping conditions (Axelsson et al., 2010), shows that despite similar formation mechanisms, several types of reservoirs are revealed: 1. Very productive reservoirs (65–877 kg/s, with productivity up to 80 kg/s/bar), due to favorable permeability and boundary conditions. These reach quasi-equilibrium at constant production (Reykir, Reykjahlid, Laugarnes (150 kg/s, 140 m water level drop), Ellidaar, Ashildarholtvatn); 2. Less productive reservoirs (15–38 kg/s, 0.7 kg/s/bar) that do not attain equilibrium. Some having favorable boundary conditions (Skatadalur, Hamar), but others require 15–25% reinjection (Laugaland) to stabilize the pressure decline. In one case a M6.6 earthquake improved productivity (Gata); and 3. Highly productive reservoirs that are plagued by cold groundwater inflow (Thorleifskot). The volume of thermal water extraction is estimated as 25–80% of the pore space volume (Laugarnes, Hamar), which explains why there are no noticeable chemical and temperature changes.

Large amounts of data have been obtained in the EGS sites of the Upper Rhine Valley graben (Sauerlach, Insheim, Beinheim, Brühl, Soultz, Bruchsal, Landau) in recent years (Schill and Genter, 2013; Genter et al., 2016), where the low temperature geothermal reservoirs occur in granites and their contacts to adjacent metamorphic units. In this case, natural fracture systems are stimulated and run (with downhole LSP pumps installed at a depth of 370 m) to sweep out heat in a closed circulation loop using duplet wells. Rhine Valley “one fracture” reservoir productivity is comparable to that of the average Icelandic reservoir: Insheim (85 kg/s at 160 °C, duplet wells 1 km apart), Beinheim (70 kg/s at 140 °C), Brühl (70 kg/s), Bruchsal (30 kg/s at 126 °C), Landau (50–70 kg/s at 160 °C), Rittershoffen (70 kg/s at 160 °C), Soultz (32 kg/s at 155 °C). Heat recovery from igneous rock units is also interesting in relation to the Paratunsky reservoir case, where two sites are underlain by diorite bodies or magma dyking systems.

ICDP's Hotspot project investigated subsurface thermal conditions in the Snake River Plain of Idaho USA using three deep coreholes (Nielson and Shervais, 2014). These holes confirmed extensive areas of low-temperature geothermal activity known from earlier drilling and utilization. Superimposed on this region of low-temperature fluids is a higher temperature (~150° C) system located at Mountain Home Air Force Base. This intermediate-temperature system is hosted by hydrothermal breccias that were formed in close to a basaltic sill that is believed to be the principal heat source (Nielson et al., 2017).

Although the Iceland, Rhine graben, and Snake River Plain examples are very useful as analogs of the Kamchatka low-temperature geothermal systems, fundamental scientific questions regarding the Paratunsky reservoirs (Figure 1) remain: 1. What is the production fracture network geometry and distribution, and how is it related to local stress conditions, lithology and natural hydraulic fracturing? 2. Where are the recharge regions, and what are the volcanic structures that recharge and transit the water into production fractures? 3. What is the reliability of the distributed TOUGH2 type models and other modeling capabilities for estimating natural hot water upflow, recharge, distribution, rates and enthalpies, reservoir permeability/capacity parameters and inflows caused by exploitation? 4. What is the potential of the Paratunsky reservoirs under downhole pumping and reinjection conditions? 5. Are there productive high-temperature geothermal reservoirs in the basement below Paratunsky LT geothermal fields at the accessible depth below 1500 m or in adjacent areas? 6. Can an array of monitoring holes be used to interpret the behavior of the Paratunsky reservoirs in the context of earthquake prediction?

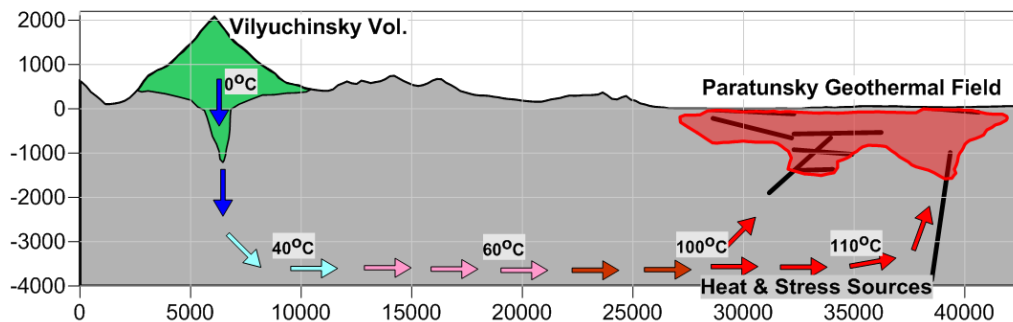


Figure 1. Model of the Paratunsky geothermal fields geo-filtration structure, recharge and boundary conditions in a cross section from Vilyuchinsky Volcano to the Paratunsky geothermal field (see Figure 3 for cross-section positioning).

We are proposing a project to ICDP to establish slim hole sampling/monitoring wells using an Atlas Copco CS-14 core rig. We have identified sites for drilling five wells to 1000 m and completing either H (96 mm hole) or N (76 mm hole) in the Paratunsky's geothermal field. Coring of these wells and subsequent integrated analysis of secondary minerals and fluid chemistry will give us a range of possible temperatures in deep recharge zones and identify potential deep reservoirs. All wells above mentioned will be converted into pressure monitoring wells in Paratunsky geothermal reservoirs to operate in a real time mode. That will benefit operating company JS “Teplo Zemli” to keep control on reservoir pressure while more submersible pumps put into operation and yield data for

large earthquakes pre-cursors study. The primary scientific objects of this project are: 1. What is the production fracture network geometry and distribution, and how is it connected to local stress conditions, lithology and natural hydraulic fracturing? 2. Where are the recharge regions and what are the volcanic structures that recharge and transit the water into production fractures? 3. What is the reliability of the distributed TOUGH2 type models and other modeling capabilities for estimating natural hot water upflow, recharge, distribution, rates and enthalpies, reservoir permeability/capacity parameters and inflows caused by exploitation? 4. What is the potential of the Paratunsky reservoirs under downhole pumping and reinjection conditions? 5. Are there productive high-temperature geothermal reservoirs in the basement below Paratunsky LT geothermal fields at the accessible depth below 1500 m or in adjacent areas? 6. Can an array of monitoring holes be used to interpret behavior of the Paratunsky reservoirs to predict a large earthquakes?

2. GLOBAL IMPORTANCE

2.1 Magma-fracking reservoirs structure of the Paratunsky geothermal fields is of interest as analogues for hard-to-recover hydrocarbon reserves and EGS.

Yellowstone magma-hydrothermal system (YNP) seems the best example of natural magma-fracking site close to existing sites of large-scale hydro-fracturing projects to yield shale oil and gas from low permeable formations. Just 300 miles apart from YNP are Bakken (3.65 Billion Bbl), Green River (1.3 Billion Bbl), Colorado Group (>300 Tcf) (Zoback, 2010). Those reservoirs are subject of massive fluid injections/extractions following hydro-fracking, that is an equivalent of magma-fracking from geomechanical point of view. Nevertheless, YNP is not available for drilling, that is why only indirect methods can be used to verify production fracture structure. On the other hand, Paratunsky reservoirs, composed of Neogene volcanogenic-sedimentary rocks (Nal, N_{1pr}) and partially settled in caldera type structures, may be considered as a reservoir analogue for the nearby (50 km to south) Mutnovsky and most other high-temperature geothermal fields (suitable for EGS) in Kamchatka, as well as analogue of production layers for Okhotsk Sea shore gas fields (Kshuksky, N-Kavakchinsky etc), - is available for drilling, and one can use direct drilling methods to verify production fracture structure here.

2.2 Active faults demonstrate predictive behavior that are pre-cursors to large earthquakes, which regularly take place in the Kamchatka shelf/subduction zone (one earthquake with M>6.0 each 9 month in average).

Here we give one example of fluid pressure sensitivity of the Mutnovsky geothermal reservoir to large earthquakes. Capillary tubing pressure monitoring (0.5 min⁻¹) was conducted during 1995-2006 (Kiryukhin et al., 2010). An earthquake of M=5.7 took place on 16 November 2004 11:57 at depth of -37 km abs at N52.96, E160.45. A pressure drop started 1.5 hours before the earthquake and reached 4.5 bars at the time of the event. Then pressure cycling occurred with an amplitude of up to 8.5 bars during 1 hr. Paratunsky reservoirs also are hosted by active geothermal production faults, but they have not been tested for pressure vs. large earthquakes sensitivity yet. However, this is most relevant since Paratunsky is closer to P-Kamchatsky city (40 km), than Mutnovsky (70 km). The primary objective of this proposal is to sample and monitor the geothermal processes in the Paratunsky field; however, with little extra effort and cost, it also provides the opportunity to test the monitoring array as a predictor of earthquake activity

3. Societal Relevance

3.1 Energy from geothermal sources.

Scientific investigation of the Paratunsky geothermal field will have important practical applications for exploration and development of low-temperature resources worldwide. Currently, the Paratunsky geothermal field serves as a source of district heating and greenhouses for the village of Paratunka (3000 inhabitants), and includes numerous balneology facilities and swimming pools. But this is not the limit of the enormous geothermal energy potential of this field because most of the production wells discharge under free-flowing conditions. Using submersible pumps for thermal water extraction may significantly increase production. Moreover, using the neighboring Mutnovsky Power Plant (62 MWe installed capacity) may not only cover pumping electricity needs but also provide feedback for additional heat production using heat pump technology. The potential heat energy market includes the cities of Vilyuchinsk (22,000 inhabitants), Elizovo (39,000 inhabitants) and Petropavlovsk-Kamchatsky (181,000 inhabitants) with a 227 MWt (7.2 PJ/year) demand.

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 (Figure 2). 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 (that is an analog of Paratunsky reservoir with comparable capacity) is included, this will completely cover all heat energy needs of the main Kamchatka consumers. This is also relevant in accordance to Federal Law of 27.07.2010 # 190-FZ «Heat Delivery» on a priority of integrated generation of electrical (Mutnovsky) and heat (Paratunsky) energy. Note, that central heating system of Petropavlovsk-Kamchatsky city is equivalent to an annual savings of 219.7 thousand tons oil (or US \$104.7 million) (Kiryukhin et al., 2019).

Drilling of the five scientific wells in Paratunsky geothermal area will help to define the areal extension of geothermal reservoirs, and evaluate the deep roots that we believe are connected to intermediate- or high-temperature reservoirs. This information will help target new exploitation wells, which may yield more heat and electrical energy. Following drilling and testing, the scientific wells will be completed and instrumented to form an array of monitoring wells.

Finally, the Paratunsky (40 km²) example may encourage geothermal applications in a low-T and intermediate-T Mega-basins like West Siberia (6 million km²) with untapped geothermal resources.

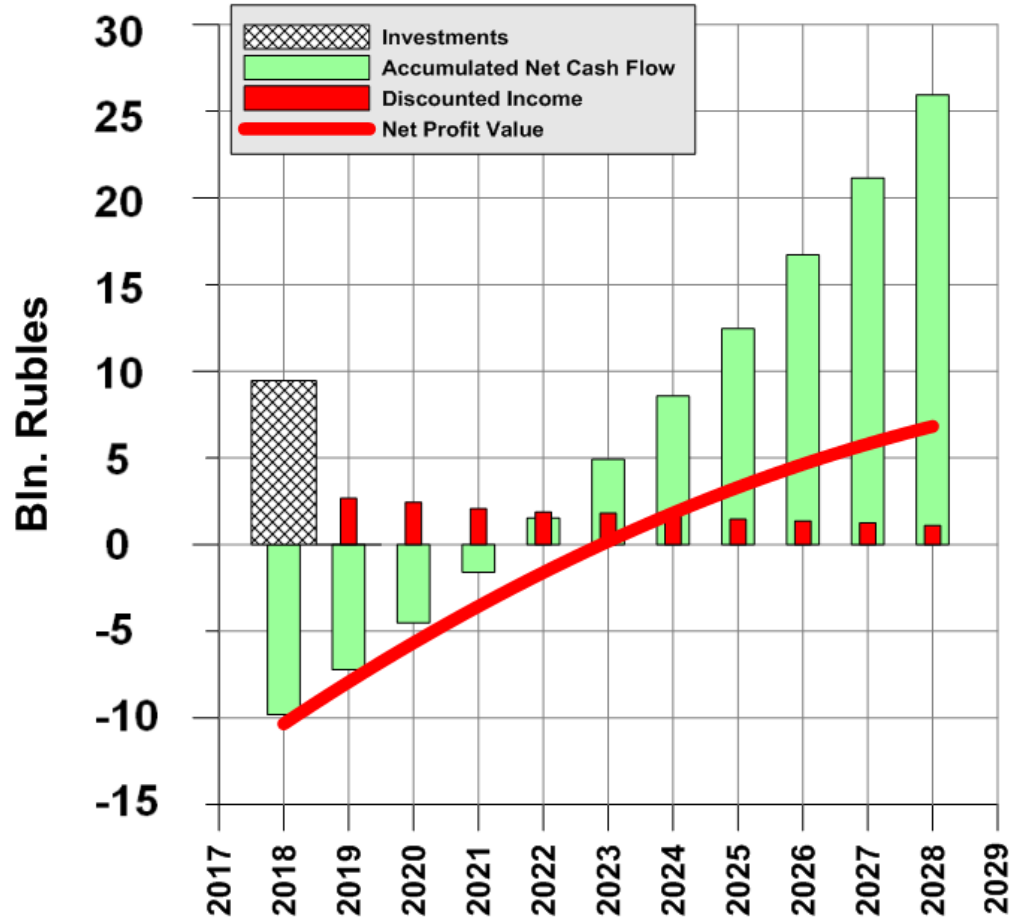


Figure 2 Net present value NPV of the project of exploitation Paratunsky geothermal field using submersible pumps (Kiryukhin et al., 2019).

3.2 Large earthquakes warning/prediction.

In accordance to long term earthquake forecast in south Kamchatka there is 40.7% probability of an earthquake with magnitude more than 7.7 during time period up to 2022 with strength of 8 points and more in Petropavlovsk-Kamchatsky (Fedotov et al., 2018). Based on this, there is necessity for urgent measures to maintain seismic and life security in Kamchatka. Paratunsky reservoir monitoring in relation to large earthquake pre-cursors study will add value to these measures.

4. EXPECTED SCIENTIFIC OUTCOMES

- 4.1 Verify TOUGH2-model derived reservoir adjacent in the east to the Paratunsky geothermal reservoir (Kiryukhin, 2017). This reservoir may comparable to the currently known Paratunsky reservoir.
- 4.2 Verify intermediate-temperature geothermal reservoirs indicated by secondary minerals observed in a recently drilled well RE-10 (laumontite) at the base of NP and N sites of the Paratunsky geothermal reservoir.
- 4.3 Understand magma fracking sources in SR site of Paratunsky geothermal reservoir and in Verkhne-Paratunsky geothermal reservoir.
- 4.4 Get experience using the Atlas Copco CS-14 coring rig that will be used in a future Mutnovsky EGS ICDP project.
- 4.5 Publish a number of papers in Journal of Volcanology & Geothermal Research, Geothermics, Geofluids etc.
- 4.6 Create a capable scientific drilling team at the Institute of Volcanology & Seismology FEB RAS.
- 4.7 Transfer magma fracking knowledge to hard-to-recover hydrocarbon projects elsewhere in the world.

5. STRATEGY FOR ADDRESSING SCIENTIFIC OBJECTIVES THROUGH DRILLING

We anticipate proposing drilling of five scientific wells up to 1000 m depth in different sites of the Paratunsky's geothermal fields (see below). Each site will be continuously cored. The holes will be flow tested and then completed as monitoring holes with the installation of real-time pressure gauges, seismic recorders and chemical detectors. Multi-well flow tests will be conducted to verify each scientific well's connectivity to the discrete production fracture network of Paratunsky reservoirs.

6. PROPOSED DRILL SITES

We have identified five sites for drilling five wells to 1000 m and complete either H (96 mm hole) or N (76 mm hole) in the Paratunsky's geothermal fields: NP, N, SR, VP and eastern NP (Figure 3) are proposed. The sites are based on knowledge of the geology and extensive TOUGH2 modeling. These sites may change following input from participants at the Workshop.

Well 1 is proposed in a central part of temperature anomaly of the N-site of the Paratunsky geothermal field. This point is proposed to be a core of ascending hot water (TOUGH2-modeling estimates are 26 kg/s and 464 kJ/kg or 111 °C). Coring of this well and subsequent integrated analysis of secondary minerals and fluid chemistry will give us a range of possible temperatures in deep recharge zones of N site.

Well 2 is proposed in a central part of temperature anomaly of the NP-site of the Paratunsky geothermal field. This point is proposed to be a core of ascending hot water (TOUGH2-modeling estimates are 70 kg/s and 415 kJ/kg or 99 °C). Coring of this well and subsequent integrated analysis of secondary minerals and fluid chemistry will give us a range of possible temperatures in deep recharge zones of NP site.

Well 5 is proposed to be drilled in a potential geothermal reservoir adjacent to the NP site of the Paratunsky geothermal field. The open eastern boundary of the production geothermal reservoir where intermediate temperature chloride water accumulated was pointed out based on TOUGH2-EOS1+tracer modeling.

Well 3 is proposed to be drilled in a central part of temperature anomaly of the SR-site of the Paratunsky geothermal field. This point is proposed to be a core of ascending hot water (TOUGH2-modeling estimates are 87 kg/s and 366 kJ/kg or 87 °C). Coring of this well and subsequent integrated analysis of secondary minerals and fluid chemistry will give us a range of possible temperatures in deep recharge zones of SR site.

Well 4 is proposed to be drilled in a central part of one of temperature anomalies of the Verkhne-Paratunsky geothermal field. Coring of this well and subsequent integrated analysis of secondary minerals and fluid chemistry will give us a range of possible temperatures in deep recharge zones of Verkhne-Paratunsky geothermal reservoir, that is composed of quartz diorites.

All wells above mentioned will be converted into pressure monitoring wells in Paratunsky geothermal reservoirs to operate in a real time mode. That will benefit operating company JS "Teplo Zemli" to keep control on reservoir pressure while more submersible pumps put into operation and yield data for large earthquakes pre-cursors study.

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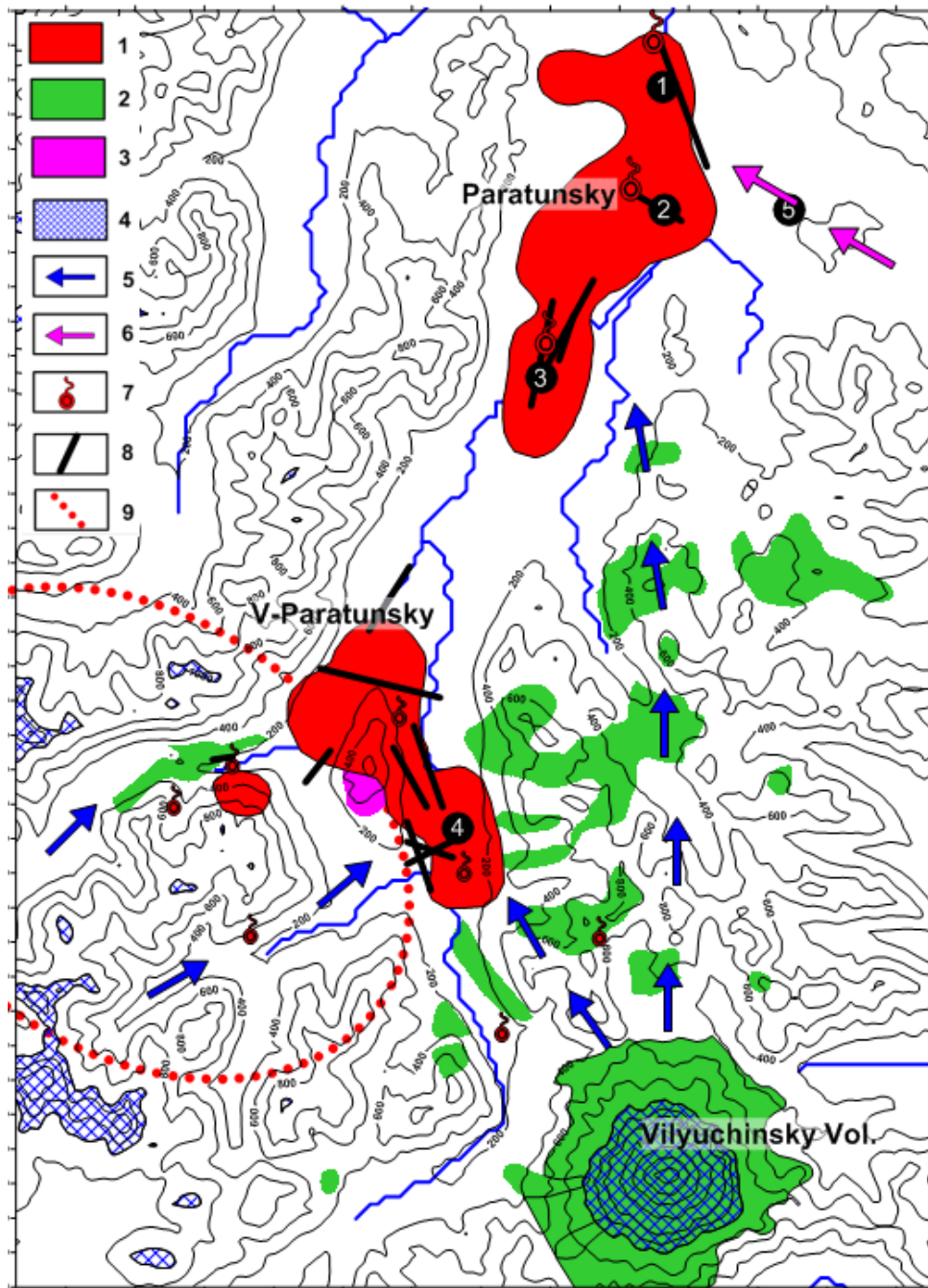


Figure 3. Proposed drilling sites in the Paratunsky geothermal fields: 1 – well 1 (N-site of the Paratunsky geothermal field), 2 – well 2 (NP-site of the Paratunsky geothermal field), 3- well 3 (SR-site of the Paratunsky geothermal field), 4 – well 4 (Verkhne-Paratunsky geothermal field), 5 – well 5 (potential geothermal reservoir, adjacent to NP site of the Paratunsky geothermal field). 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 – Caldera rim 1.2-1.5 MY (Leonov et al., 2007).

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