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Thermal and permeability structure and recharge conditions of the low temperature Paratunsky geothermal reservoirs in Kamchatka, Russia

A.V. Kiryukhin[a,*], L.A. Vorozheikina[b], P.O. Voronin[a], P.A. Kiryukhin[c]

[a] *Institute of Volcanology & Seismology FEB RAS, Piip 9, Petropavlovsk Kamchatsky 683006, Russia*
[b] *JS "Teplo Zemli", Paratunskaya St., Termalny 684035, Russia*
[c] *Exigen Services, Pulkovskoe 40-1, Saint-Petersburg 196158, Russia*

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ABSTRACT

The Paratunsky low temperature geothermal field has been operating since 1964. During the period of exploitation from 1966 to 2014, 321 Mt of thermal water (Cl-Na, Cl-SO_4-Na composition, M up to 2600 ppm) with temperatures of 70–100°C was extracted and used for district heating, balneology and greenhouses. The structure of the 40 km^3 Paratunsky low temperature (80–110 °C) geothermal volcanogenic reservoir was geometrically characterized, hot water upflow regions and the 3D permeability distribution were identified with hydrogeological data, and the distribution of the feed zones and 3D temperatures were constrained by 3D spline approximation. Water isotope and gas (N_2, 96–98%) data analysis indicated that the main recharge region of the Paratunsky geothermal reservoirs is the Viluychinsky Volcano (2173 masl) and 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 Viluychinsky Volcano's recharge region).

TOUGH2 modeling of the thermo-hydrodynamic natural state and the history of exploitation (involving pressure, temperature and chemical changes response to utilization) between 1965 and 2014 yield estimates of hot water upflow rates (190 kg/s), the production reservoir compressibility (up to $4 \times 10^{-8}\ Pa^{-1}$) and permeability (up to 1.4 D). Modeling confirmed areal discharge of the thermal water from the production reservoir in the top groundwater aquifer (top Dirichlet boundary conditions). Modeling of the chemical (Cl-) history of exploitation provides an explanation of gradual Cl- accumulation due to the inflow of chloride-containing water through the eastern (open) boundary of the geothermal reservoirs. Modeling of the long-term exploitation until 2040 with an exploitation load of 256 kg/s merely shows a low pressure drop (0.7 bar) and an insignificant drop of temperatures in the production geothermal reservoir of the Paratunsky geothermal field.

1. Introduction

Low temperature geothermal fields, which are defined by reservoir temperatures below 150 °C at a depth of 1 km (Rybach, 1981; Axelsson and Gunnlaugsson, 2000; Johannesson, 2016) have experienced decades of industrial utilization in Iceland, Hungary, China, Turkey, France, Germany, Russia and other countries. This has yielded experience for inferring the mechanisms of formation of such fields, including heat and water recharge conditions in the natural state and under exploitation, reservoir properties and renewability potential estimates, etc. Moreover, 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 Laugarness). Note, that by 2016, Reykjavik heating system was also added by a total of 450 MWth from Nesjavelir and Hellysheidi high temperature geothermal fields CHP (Johannesson et al., 2016).

In this paper, we studied the low temperature Paratunsky geothermal fields in Kamchatka (Far East Russia), which are adjacent to active volcanic regions (Fig. 1) and are composed of volcanogenic rocks, such as the abovementioned Icelandic fields. The currently approved conceptual model of low temperature geothermal systems assumes deep circulation of meteoric water, originating from the highlands of the recharge region, mining heat from deep fracture/dykes roots, and then ascending in the form of hot springs discharge in a lowland (Bodvarsson, 1983). 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

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* Corresponding author.
E-mail address: avkiryukhin2@mail.ru (A.V. Kiryukhin).

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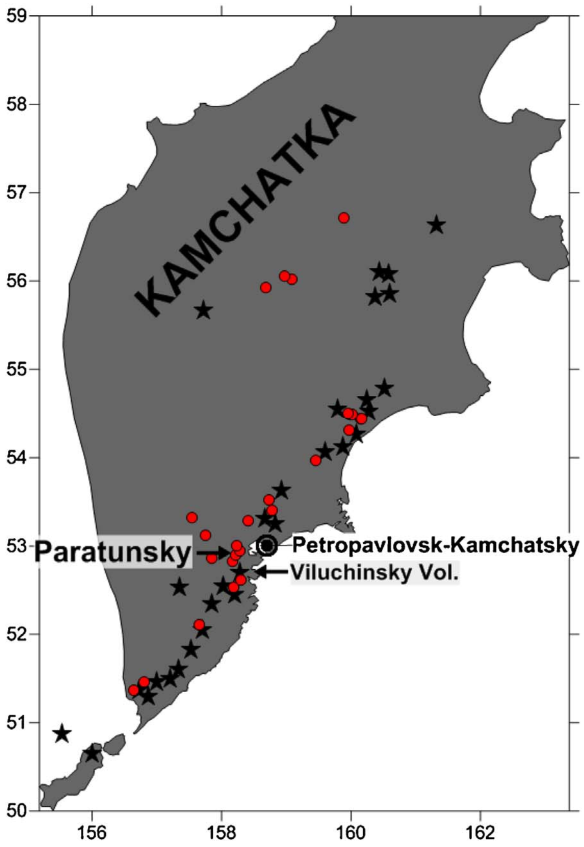

Fig. 1. Location of the Paratunsky geothermal fields in the structure of volcanoes (stars) and major geothermal discharge regions (filled circles) in Kamchatka.

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, they 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 (Skatudalur, Hamar), but others needing treatment in the form of 15–25% reinjection (Laugaland) to stabilize the pressure decline, in some cases an M6.6 earthquake may improve productivity too (Gata); and 3. Highly productive reservoirs, but 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 in most of the systems.

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.

Although Iceland and Rhine graben examples are very useful as analogs of the Kamchatka low temperature geothermal systems, fundamental and specific questions (regarding the Paratunsky reservoirs) remain: 1. What is the production fractures network geometry and distribution, and how is it connected to local stress conditions, lithology and natural hydraulic fracturing? 2. Where are the highlands recharge regions and what are the volcanic structures that recharge and transit the water into production fracture roots? 3. What is the reliability of the distributed TOUGH2 type models and other modeling capabilities for estimating natural hot water upflow recharges, distribution, rates and enthalpies, reservoir permeability/capacity parameters and inflows caused by exploitation? 4. What is the reservoir sensitivity to the time-dependent (seasonal) top discharge boundary conditions? 5. What is the potential of the Paratunsky reservoirs under downhole pumping and reinjection conditions?

Regional hydrogeology and geothermal problems related to the Paratunsky hydrothermal system, especially the conditions of its formation, were discussed in Manukhin and Vorozheikina's paper (1976). During the following 40 years, significant exploitation of the Paratunsky geothermal field was achieved, new data on transient pressures, temperatures and chemical composition variations during the 1966–2014 exploitation period were obtained, and the total mass of extracted thermal water was 321 Mt. Currently, new TOUGH2 modeling methods of geothermal reservoirs are being broadly implemented (Pruess et al., 1999; Finsterle, 1999, 2014).

This prompts us to return to the analysis of the fundamental problems of formation of the hydrothermal systems and their above-mentioned exploitation, using the Paratunsky geothermal fields as an example. In addition, the forecast of exploitation of the Paratunsky geothermal fields may have important practical applications for Kamchatka. The Paratunsky geothermal fields serve as a source of district heating and greenhouses for the village of Paratunka (3000 inhabitants), and numerous balneology facilities and swimming pools, but this is not the limit of the enormous geothermal energy potential of these geothermal fields, because most of the production wells are discharges in free flow condition. Using submersible pumps for thermal water extraction may significantly increase the production flowrate. Moreover, using neighboring Mutnovsky PPs (62 MWe installed capacity, while this is not in a full load demand) 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 Petropavlosk-Kamchatsky (181,000 inhabitants) with a 227 MWt (7.2 PJ/year) demand.

2. Hydrogeological stratification

According to the results of exploratory drilling mainly to the depth of 1000–1500 m, the following hydrogeological stratification was found for this field:

Unit 1 – alluvial sand and gravel-pebble deposits (the host reservoir of a powerful stream of cold groundwater);

Unit 2 – Lower Quaternary siltstones interbedded with fine-grained sandstones (a caprock of geothermal reservoir) at a depth of 40–180 m, and their thickness varies from 10 to 150 m;

Unit 3 – lower Quaternary conglomerates with interbedded siltstones and tuff stones (which form the upper aquifer of thermal water), their thickness of 150 m;

Unit 4 – tuff stones, tuff conglomerates and tuffs of the Alneysky series (which occur only in the northern region);

Unit 5 – tuffaceous pyroclastic rocks of the Paratunsky Formation (characterized by the highest productivity) are the main hydrothermal host rocks;

Unit 6 – intrusive rocks (low productivity, except for some tectonic zones), below of 1200–1350 m depth.