Thermo-hydrodynamic model of the Koshelev geothermal system, Kamchatka, Russia

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Abstract. The results of numerical thermo-hydrodynamic simulation of Koshelev geothermal system are presented. The question of the possibility of the existence of a shallow geothermal reservoir at the Lower-Koshelev thermal field is briefly investigated. The simulation results refute the assumption of the existence of a near-surface geothermal reservoir. It is more likely that in this part of the geothermal system there is a region of permeable rock that is relatively narrow in cross section and which performs the function of a conduit. The size and shape of the apical part of the steam zone under the Lower-Koshelev thermal field are controlled by the diameter of the conduit. Results of simulations with a conduit diameter of 1200 and 500 m are presented. The latter is more likely, since it best matches the field data.

1. Introduction
The Koshelev geothermal system is located in the southern part of the Kamchatka Peninsula, 15 km east of the Sea of Okhotsk coast (Figure 1). Estimates of the electric power vary by different estimates from 87 [1] to 279 MW [2]. On the surface, the geothermal system is manifested by intensive discharging on Lower-Koshelev and Upper-Koshelev thermal fields.

The Lower-Koshelev thermal field is located on a relatively gentle slope at altitudes of 700–800 m. The area of the field according to the isotherm of 20 °C at a depth of 0.5 m is about 38000 m² [3]. Thermal manifestations are represented by hot springs with temperatures up to 76 °C and powerful steam jets up to 0.7 kg/s with the maximum temperature of 127 °C.

Upper-Koshelev thermal field is located on subvolcanic formations in the erosion crater at altitudes of 1100–1300 m [3, 4]. The field inclines to the west with a difference in elevation of 40–50 m. The area of the field according to the isotherm of 20 °C at a depth of 0.5 m is about 303000 m² [3]. The most characteristic form of thermal manifestations are powerful jets of superheated steam with a flow rate of 0.1–0.4 kg/s, a temperature of 120–153 °C, and steam velocity - over 100 m/s [3]. There are more than 40 such jets, and the number of smaller ones amounts to hundreds. In places where steam jets are flooded with surface water or their own condensate, boiling funnels and small lakes form, which evolve into mud pots with subsequent blockage or formation of mud volcanoes. Several hot springs with a temperature of 73–96 °C were recorded in the field [3].
2. Brief geological characteristic

In the area of the Koshelev geothermal system, geophysical methods revealed a large crustal depression of the northeast strike. The structure of the depression is most clearly manifested in the relief of the Cretaceous basement (Figure 1), built on the basis of a complex interpretation of seismo-gravimetric data [5]. The roof of the Cretaceous basement within the limits of this depression submerges to a depth of 3–3.5 km. The faults of the north-eastern strike limit the extended graben, which coincides with the Cretaceous basement depression in the area of the Koshelev system [5]. The faults of the north-east and north-north-east strike correspond to the north-west border of the depression and determine the general localization of the Koshelev geothermal system [5].

Thermal manifestations within the geothermal system trace smaller sublatitudinal faults, which have intersecting direction in relation to the deep fault, limiting the Cretaceous basement depression [5]. So, the outgoing channels of the Lower-Koshelev thermal field are connected with the intersection of faults of the sublatitudinal and north-east strike [3]. Upper-Koshelev and Lower-Koshelev fields and Sivuchinsky hot springs are located in a single sublatitudinal geothermal fault zone with a width of about 2 km and a length of about 10 km, which determines the deposit area [1, 4]. All powerful thermal manifestations of the system are connected by this zone with the subsoil of the geothermal system. Eruptive centers migrated along this zone [3, 7–10], steam jets and hot springs were connected to it [1, 3, 4, 6, 7]. The zone is characterized by increased permeability and is fixed by hydrochemical anomalies and abnormally high concentrations of CO₂, CH₄ and Rn in the soil gas [1, 7]. It is also traced by a band of local negative magnetic anomalies and anomalously low geoelectric resistance [7].
3. Thermo-hydrodynamic models

3.1. General models description

The modeling area is a rectangular parallelepiped, 17 km in size in the latitudinal direction, 6.8 km in the meridional direction and 9.3 km in the vertical direction (Figure 2). The lower boundary of the modeling area is a horizontal plane at a depth of 7400 m below sea level. The upper limit of the models is set so that the maximum in the relief of the area of 1853 m falls into the modeling area. This is the plane at an altitude of 1864 m above sea level.

Figure 2. Modeling area and computational grid. Legend: 1 - thermal fields (1 - Lower-Koshelev, 2 - Upper-Koshelev); 2 - Sivuchinsky hot springs; 3 - the boundary of the magma chamber; 4 - boundaries of subvolcanic intrusions; 5 - boundaries of tectonic fault zones; 6 - conduits of thermal fields.

Three-dimensional numerical thermo-hydrodynamic models of the Koshelev geothermal system are based on an analysis of the available data on its geological structure [1, 3, 4–7, 11–13] and the physical properties of rocks [14–21]. The structure of the models in the section is shown in Figure 3. Physical properties of rocks, except permeability, are given in table 1. Domain permeability is a variable parameter and different in each model.

Figure 3. Domains of rocks and computational grid. On the left the section through the center of the Upper-Koshelev thermal field. On the right the section through the center of the Lower-Koshelev thermal field.

To build thermo-hydrodynamic models of a geothermal system, information about the source of its heat supply is needed. Therefore, before building models of the geothermal system, the size of the magma chamber was evaluated first. The radius of the magma chamber under the Koshelev volcanic massif was estimated at 2.8 km [22]. Below, this value is used to specify an ellipsoidal magmatic
source of equal size in thermo-hydrodynamic models, since according to the available data [3], the sublatitudinal fault zone is saturated with melted material.

### Table 1. Properties of rock domains.

| Domain number | Thermal conductivity (W/m·K) | Specific heat (J/kg·K) | Density (kg/m³) | Compressibility (×10⁵ MPa⁻¹) | Porosity (%) | Annotation |
|---------------|------------------------------|------------------------|-----------------|-------------------------------|--------------|------------|
| 1             | 2.73                         | 832                    | 2540            | 3.50                          | 10.0         | Cretaceous basement |
| 2             | 2.38                         | 832                    | 2540            | 3.50                          | 10.0         | Berezovsky formation |
| 3             | 1.53                         | 1089                   | 2620            | 2.25                          | 2.6          | Alneya and Pauzhetsky formation |
| 4             | 1.55                         | 1106                   | 2630            | 2.28                          | 2.6          | Volcanic bodies |
| 5             | 2.15                         | 867                    | 2900            | 1.55                          | 8.7          | Subvolcanic intrusion under the Lower-Koshelev field |
| 6             | 2.15                         | 867                    | 2900            | 1.55                          | 8.7          | Subvolcanic intrusion under the central part of the massif |
| 7             | 1.55                         | 1106                   | 2630            | 2.28                          | 2.6          | Lower-Koshelev conduit |
| 8             | 1.55                         | 1106                   | 2630            | 2.28                          | 2.6          | Upper-Koshelev conduit |
| 9             | 2.38                         | 832                    | 2540            | 3.50                          | 10.0         | Rocks of the Berezovsky formation within tectonic fault zones |

The boundary conditions are given as follows. At the lower and lateral boundaries of the simulation region, there is no heat and fluid flow. On the surface defined constant temperature of 10 °C and a constant atmospheric pressure. The area of the magma chamber is specified by a boundary condition with a constant temperature of 900 °C. The initial temperature distribution is given by an average geothermal gradient of 30 °C/km. The initial distribution of fluid pressure is hydrostatic. The modeling time is 40 thousand years. The spatial discretization of the model was made using a rectangular grid measuring 71×28×55 cells with an irregular steps of 100–500 m. In total, the model contains 109340 blocks.

Geothermal fluid is assumed as pure water in different phase states. For thermo-hydrodynamic simulation of geothermal fluid parameters, the HYDROTHERM program [23] was used. It is capable of producing numerical three-dimensional modeling of heat and mass transfer processes in a porous medium in the temperature range of 0–1200 °C and pressures of 0.05–1.000 MPa, which allows its use in supercritical conditions. The program was used to simulate heat transfer under supercritical conditions in rocks of a number of geothermal systems in the world associated with volcanoes: Kuju [24] and Unzen [25, 26] in Japan, Merapi in Indonesia [27], Mayon in the Philippines [28], Cascade Range in the USA [29] and Mutnovsky [30] in Russia, Kamchatka.

### 3.2. The assumption of a shallow geothermal reservoir

In [4, 7] it is indicated that under the Lower-Koshelev field there are intrusive dome-shaped body of 300–1000 m along different sections. Its roof was opened at a depth of 200–400 m. It is noted that its length from west to east is at least 4–5 km. Age is estimated as lower – middle pleistocene. This intrusion is represented by domain 5 in the models. It is possible that fractures could have occurred there during cooling. Thus, it is likely that a vast area of permeable rock may be located at a shallow depth under the Lower-Koshelev thermal field. This area of permeable rock could play the role of a geothermal reservoir.

In order to simulate the presence of a shallow hydrothermal reservoir near the surface under Lower-Koshelev field, the permeability of the subvolcanic intrusion was increased in this model...
(domain 5). The permeability of all domains is shown in table 2. The simulation results are shown in figure 4.

### Table 2. Permeability of rock domains.

| Domain number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Permeability (m$^2$) | $1 \times 10^{-16}$ | $1 \times 10^{-16}$ | $1 \times 10^{-16}$ | $1 \times 10^{-15}$ | $1 \times 10^{-14}$ | $1 \times 10^{-15}$ | $1 \times 10^{-16}$ |

![Figure 4. Distribution of temperature (°C) and phase state of the fluid. On the left the section through the center of the Upper-Koshelev thermal field. On the right the section through the center of the Lower-Koshelev thermal field.](image)

The results of the thermo-hydrodynamic simulation of this model demonstrate that an increase in the permeability of rocks in the volume of subvolcanic intrusion leads to excessive heating and the formation of a continuous steam zone near the surface over a wide area. This is contrary to the actual available data.

#### 3.3. Direct conduit at the Lower-Koshelev field

Using preliminary numerical experiments, a thermo-hydrodynamic model was created, which correctly reproduces the areas of superheated steam and steam-water zones near the surface in the same areas where the actual hydrotherms in both thermal fields occur simultaneously. For this, about 40 numerical experiments on models were performed, each of which consistently approached an adequate representation of the Koshelev geothermal system. As a result, a base model was obtained, which is used to estimate the distribution of thermo-hydrodynamic parameters of the fluid in the system. The diameter of the conduit on the Lower-Koshelev thermal field is 500 m. The permeability of all domains is given in table 3. The simulation results of the basic model are presented in figure 5.

### Table 3. Permeability of rock domains.

| Domain number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Permeability (m$^2$) | $1 \times 10^{-16}$ | $1 \times 10^{-16}$ | $1 \times 10^{-16}$ | $1 \times 10^{-15}$ | $1 \times 10^{-14}$ | $1 \times 10^{-15}$ | $1 \times 10^{-16}$ |

In areas adjacent to the magma chamber, the geothermal fluid is supercritical. In the immediate vicinity of the surface there are steam zones, the discharging of which form the Lower- and Upper-Koshelev thermal fields. The results of thermo-hydrodynamic simulation demonstrate a qualitative correspondence to the actual data near the surface. Thermal anomalies and steam zones are correctly localized in the model under the areas where the thermal fields are actually located.
3.4. Increased conduit diameter

This thermo-hydrodynamic model is similar to the previous one. The only difference is that the diameter of the conduit of the Lower-Koshelev thermal field is increased to 1200 m. The issue of the ability of the thermo-hydrodynamic model to correspond quantitatively with the field data in the presence of a direct conducting channel between the magmatic chamber and the surface is considered. The permeability of all domains was listed in table 3. The simulation results are shown in figure 6.

The model is able to demonstrate a high-quality compliance with field data. It simulates separate thermo-anomalies and vapour zones on the Lower- and Upper-Koshelev thermal fields. But in the Lower-Koshelev, a somewhat larger steam zone and a width of the isotherm uplift front demonstrate than on similar models with a channel diameter of 500 m, which better correspond to the field data.

4. Conclusions

Thermo-hydrodynamic simulation shows that if there was a laterally extended geothermal reservoir within the subvolcanic intrusion near the surface on the Lower-Koshelev thermal field, this would cause too intense heating of rocks and would lead to the emergence of too large shallow steam zones. It is more likely that in this part of the geothermal system there is a region of permeable rock that is relatively narrow in cross section and which performs the function of a conduit.

The size and shape of the apical part of the steam zone under the Lower-Koshelev thermal field are controlled by the diameter of the conduit. In the model with conduit diameter of 500 m, the steam zone is simulated, which better corresponds to the actual upper boundary of the steam zone [4], outlined by the results of drilling operations. It was noted in [4] that the lower boundary of this zone was not established, but it was assumed that steam could be generated at a depth of at least 2.5–3 km. This
assumption is confirmed by thermo-hydrodynamic simulation (Figure 5). In general, the results of the simulation demonstrate compliance with the available data both from the surface, and obtained by drilling exploration wells. This suggests that this model adequately represents the Koshelev geothermal system, and the set values of the input parameters are close to real.

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