THE THERMAL HYDRODYNAMIC MODEL OF THE PAUZHETKA HYDROTHERMAL SYSTEM (SOUTH KAMCHATKA, USSR)

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ABSTRACT

The Pauzhetka hydrothermal system is located in a volcano-tectonic depression near active volcanic centers. Temperatures at depths of 300 to 800 m are 180 to 210°C. The natural discharge of the hydrothermal system includes the discharge of the Pauzhetka springs, a concealed discharge in the bed of the Pauzhetka River (95 kg/s), and steam discharge in the Kambalny Ridge (15 kg/s). Only the upper part of the geothermal reservoir was penetrated by drillholes (to 1200 m); therefore, we have used a mathematical model to assess the conditions of water and heat feeding the hydrothermal system.

BRIEF INFORMATION ON THE PAUZHETKA HYDROTHERMAL SYSTEM

The Pauzhetka hydrothermal system (Figure 1) involves the Pauzhetka springs (35 kg/s) and the Kambalny steam grounds (15 kg/s). The area covering the Pauzhetka hydrothermal system has a form elongated in the northwest direction, and a size 10 km long and 2 km wide. Structurally the hydrothermal system is confined to the northwest-trending fracture zone located within the volcano-tectonic depression. Numerous rhyolitic and dacitic extrusions and pumice deposits of Holocene age in this region (including the Dikiy Greben volcano extrusion with a volume of 30 km^3) attest unanimously to the existence at a shallow depth of a magma body, which may be considered as the source of heating of the hydrothermal system.

The recharge area of the Pauzhetka hydrothermal system includes a zone of the Kambalny Ridge (except for the area of steam ground discharge) through which the zone of tectonic fracturing is traced, and the area adjacent to the east with a few lakes lying at 100 to 200 m elevation. The intensity of water infiltration in the volcanic regions of Kamchatka is 10 to 20 kg/s km^2.

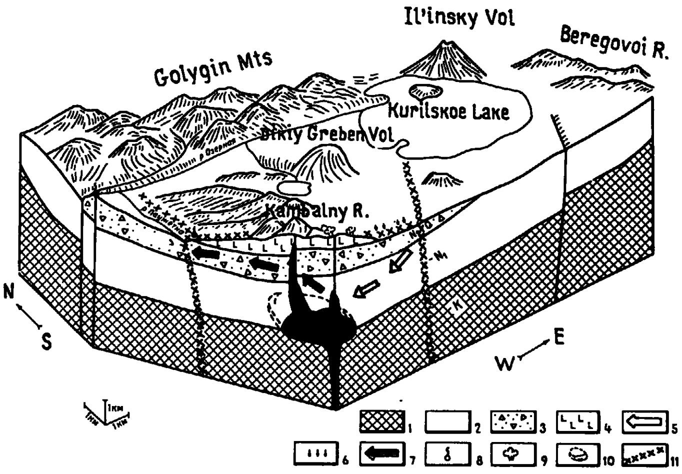

Figure 1. Block diagram of the geological structure of the Pauzhetka hydrothermal system. Geological structure: 1 = Cretaceous metamorphic rocks; 2 = Paleogene-Neogene volcanogenous-sedimentary rocks formed predominantly in marine conditions; 3 = volcanogenous-sedimentary rocks of Pliocene-Quaternary age, with tuffs formed predominantly in lacustrine and terrestrial conditions; 4 = volcanoes of the Kambalny Ridge. Hydrogeological conditions: 5 = direction of movement of cold, infiltrating waters; 6 = zones favourable for infiltration; 7 = direction of movement of thermal waters; 8 = thermal springs; 9 = steam grounds; 10 = source of heat, assumed magma chamber; 11 = permeable zones of tectonic fracturing for underground waters.

Since 1966 the 11 MW power plant has operated on the base of the Pauzhetka geothermal system; the withdrawal for its operation averages 150 kg/s. In 1962-1963, as well as in 1975-1976, well tests were conducted with a discharge of 128 kg/s and 200 kg/s, respectively. Analyses of pressure decline in the reservoir were made by Sugrobov (1965, 1976), Voronkov (1983) and Kiryukhin (1984);

direct estimation of the surface thermal capacity of the hydrothermal system and thermal conductivity of rocks composing this system were made by Sugrobov (1976). As a result it has been determined that:

(1) The natural discharge of the hydrothermal system averages 130 to 150 kg/s. The minimum assessment is based on the discharge of the Pauzhetka springs including a concealed discharge in the bed of the Pauzhetka River (95 kg/s) and the steam discharge in the Kambalny Ridge (15 kg/s), in total constituting 110 kg/s. This assessment was also proved by a stationary hydrodynamic regime during well tests in 1962-1963 with a discharge of 128 kg/s. The maximum assessment is proved by nonstationary hydrodynamic and heat regime during well tests in 1975-1976 with a discharge of 200 kg/s and during exploitation with a discharge exceeding 150 kg/s.

(2) The pressure decline during exploitation and well tests is in accordance with the filtration scheme "layer of unconfined thickness," which reflects the absence of impermeable layers within the limits of the hydrothermal system and its confinement to the permeable deep fracturing zone. On the whole the coefficient of hydraulic conductivity of this zone is 200 to 600 m^2/day.

(3) In the area 2 x 3 km adjacent to the Pauzhetka springs the hydrothermal system was penetrated by 60 wells up to depths of 1200 m. As a result, the form of the thermal anomaly in the Pauzhetka geothermal reservoir became partly known. Temperatures at depths reach 225°C, averaging 180 to 210°C. The thermal anomaly has a form 2 km wide elongated in a northwest direction (parallel to the homogeneous tectonic fracturing).

(4) The coefficient of thermal conductivity of rocks composing the hydrothermal system for the upper part of the reservoir is 2 to $5 \cdot 10^{-3}$ cal/cm s °C.

THERMAL HYDRODYNAMIC MODEL

In order to assess the conditions of the formation of water and heat feeding the Pauzhetka hydrothermal system, a numerical thermal hydrodynamic model was used. Its characteristics are given below and shown in (Figure 2).

(1) The model is two-dimensional, taking into consideration that the hydrothermal system is confined to a linear zone of tectonic fracturing with a northwest trend.

(2) The water and rocks are supposed to be in a state of thermal equilibrium.

(3) Fluid filtration is supposed to be one-phasal, because the hydrostatic pressure at depths of 3 to 5 km (where the largest temperature fluctuations are possible) exceeds the critical steam pressure, 225 bar.

(4) The filtration is taken to be stationary at each time step.

(5) The coefficients of heat conductivity, heat capacity, filtration and thermal expansion of water are taken to be constant, independent of temperature and pressure.

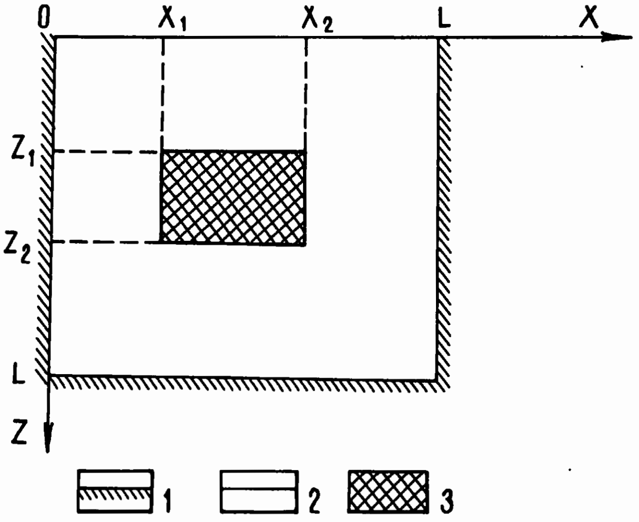

Figure 2. Schematization of thermal hydrodynamic conditions of the Pauzhetka hydrothermal system. 1 = hydraulically impermeable boundaries; 2 = hydraulically permeable boundaries at which water exchange with surface waters occurs; 3 = source of heat.

(6) Temperature T and stream function ψ are used as the parameters of the state of the system.

(7) The area of modelling represents a rectangle, the vertical and lower sides of which are taken as hydraulically impermeable; the water exchange with surface waters is set to occur on its upper side; the temperature conditions at all boundaries are taken to be constant taking into account their remote distance from the area of greatest temperature fluctuations.

(8) A cooling magma chamber is taken to be the source of heat feeding the hydrothermal system. The heat effect of this magma chamber is defined by using the corresponding initial conditions (the model of instantaneously originating intrusion) since this magma chamber is supposed to have emerged fairly rapidly 6000 years ago. Its size may be estimated based on the volume of the Dikiy Greben volcano ($\Omega = 30$ km^3).

For the two-dimensional model the magma chamber or the heat-feeding source is schematized as a rectangle with cross section S:

$$S = (X_2 - X_1) \cdot (Z_2 - Z_1) \approx 0.5 \div 2.5\ \Omega \qquad (1)$$

Mathematically, the thermohydrodynamic model may be represented as a system of differentiated equations expressing the laws of energy, mass and moment conservation:

$$C \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right) - C_o V_x \frac{\partial T}{\partial x} - C_o V_z \frac{\partial T}{\partial z} \qquad (2)$$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} = - K \rho_o \alpha \frac{\partial T}{\partial x} \qquad (3)$$

$$V_x = - \frac{\partial \psi}{\partial z} \qquad V_z = - \frac{\partial \psi}{\partial x} \qquad (4)$$

The boundary stream function conditions may be defined as

$$\psi|_{x=L,\, x=0,\, z=0} = 0 \qquad \psi|_{z=0} = \psi_0 (x) \tag{5}$$

where the function ψ_0 (x) reflects the above-described conditions of water feeding the hydrothermal system. Max ψ_0 (x) is the total value of infiltration feeding and 2/L max ψ_0 (x) is its average value in the recharge zone. The boundary temperature conditions are expressed as

$$T|_{z=0} = 0 \qquad T|_{x=0,\, x=L} = G \cdot Z \qquad T|_{z=L} = G \cdot L \tag{6}$$

The initial temperature conditions are expressed as:

$$T|_{t=0, x,z \in [x_1 x_2] [z_1 z_2]} = G \cdot Z \quad T|_{t=0, x,z \in [x_1 x_2] [z_1 z_2]} = T_2 \tag{7}$$

From equation (3) it follows that the initial conditions for the stream function are unanimously defined by the initial temperature distribution. The system of equations (2-7) was solved by the finite-difference method on digital computer EC 1033.

The numerical parameter values used in one variant of modelling, in conventional dimensions used by hydrogeologists, are given below. In addition, the corresponding values for nondimensional parameters Ra, Fo, Fe and In characterizing this model most completely also are listed.

$C_0 = 0.3$ cal/g°C
$\lambda = 6 \cdot 10^{-3}$ cal/cm s °C
$kL = 200\ m^2$/day
$\alpha = 10^{-3}\ °C^{-1}$
$\rho_0 = 1\ g/cm^3$
$C = 0.6$ cal/cm^3°C
L = 10 km
$X_1 = 3.5$ km
$X_2 = 6.5$ km
$Z_1 = 3$ km

$Z_2 = 6$ km
$S = 9\ km^2$
$G = 0.03$ °C/m
$T_2 = 1000$°C
$t_1 = 6000$ yr
$\psi_o(x) = 3.2 \cdot x(x-10)$ kg/s km
$\max \frac{2\psi_0(x)}{L} = 15$ kg/s·km^2
In = 40
Ra = 1000
Fe = 0.09
$Fo = 2 \cdot 10^{-3}$

RESULTS OF CALCULATIONS; DISCUSSION

The results of the calculations may be expressed as a succession of temperature and hydrodynamic fields referred to different periods of time that have passed from the moment of the origin of the magma body (Figure 3). Now we shall consider this succession. Before the emergence of the body ($t < 0$), temperature increased linearly with depth in accordance with the gradient G (Figure 3.1). The groundwater flow conditions in the considered permeable zone are defined by recharge to the right side (which imitates the eastern slope of the Kambalny Ridge and regions adjacent to the east) and by discharge from the left side (which imitates the valley of the Pauzhetka River) (Figure 3.2).

Then the "instantaneous" emergence of the magma body occurs (Figure 3.3). This is reflected in a new structure of groundwater flows owing to free convection (Figure 3.4). Two thousand years after the emergence of the heat source the amplitude of freeconvection attenuates because of magma-body cooling; therole of forced convection increases (Figure 3.6); the temperature anomaly rises slowly (Figure 3.5). The most recent of the thermohydrodynamic fields (Figures 3.7, 3.8), which refers to time t + 6000 years, corresponds in time to those thermohydrodynamic conditions that now exist in the Pauzhetka hydrothermal system and therefore this field may be used for calibration of our model.

This calibration was made by comparison of calculated and actual temperature fields (Figure 3.9). The initial size of the magma chamber (heat source), S, was used as a calibration parameter. The best agreement between the calculated and actual temperature fields (the coincidence of the 200°C isotherm) was obtained by varying this parameter when S + 9 km^2. However, the calculated temperature gradient has proved to be higher than the actual one. This is apparently related to the fact that in this model we do not take into account the dependence of the specific heat of water, C_0, upon the temperature (an average C_0 value was used for the whole range of temperature fluctuations). With decreasing temperature, C_0 increases up to 1 cal/g and this must result in decreasing $\partial T/\partial Z$ in a stream tube along which the convective heat flow occurs.

The calculated discharge of groundwater flow in the hydrothermal system is 75 kg/s per 1 km of the width of this flow, and by the moment t + 6000 years forced convection predominates. If the width of hydrothermal flow is taken to be 2 km, then its discharge equal to 150 kg/s will provide the natural discharge of the hydrothermal system. This gives one more argument for the validity of this model. Thus, this model provides a thermohydrodynamic picture (Figures 3.8, 3.9) of the heat and water feeding conditions of the Pauzhetka hydrothermal system.

CONCLUSIONS

(1) In order to understand the heat and water feeding conditions of the Pauzhetka hydrothermal system a two-dimensional numerical, vertical thermohydrodynamic model was used. This model was calibrated by comparison of calculated and actual thermohydrodynamic fields at the explored site of the hydrothermal system. The size of the heat source imitating the magma chamber that emerged 6000 years ago at a depth of 3 to 6 km was taken as a calibration parameter. The heat source with a volume of 18 km^3 provides a satisfactory agreement between the calculated and actual thermohydrodynamic fields. The size of the heat source agrees well with the volume of volcanic rocks erupted in the Holocene. The water feeding the hydrothermal system at present is caused by forced convection due to infiltration recharge.

(2) The thermohydrodynamic model may be improved upon by considering the heterogeneous conditions caused by the existence of a magma body and by relaxation of permeability with depth, the dependence of the specific heat of water upon the temperature, and steam effects in the upper part of the reservoir.

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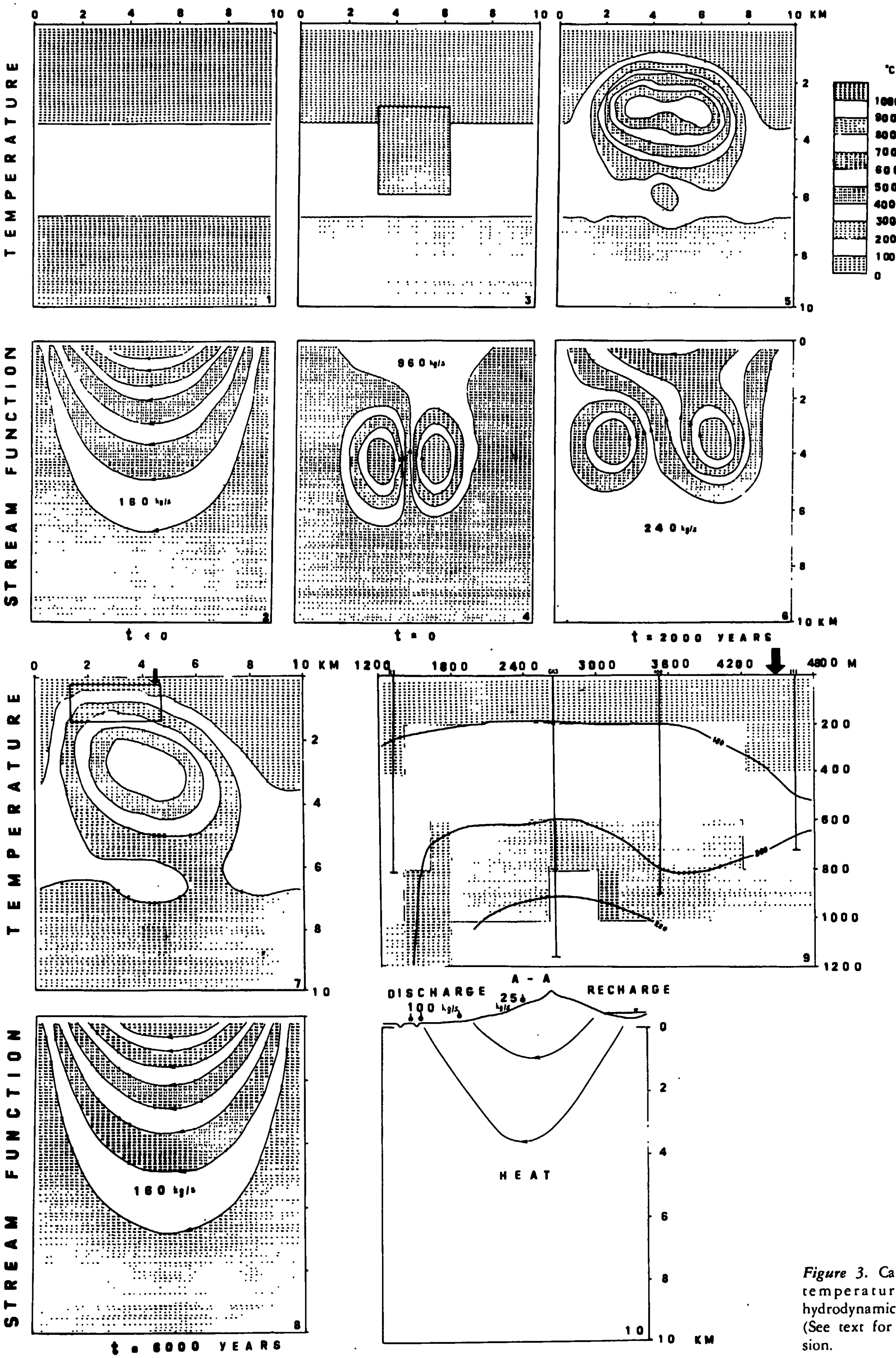

Figure 3. Calculated temperature and hydrodynamic fields. (See text for discussion.

NOMENCLATURE

X,Z = space coordinates

$X_1X_2Z_1Z_2$ = space co-ordinates defining the location of the heat-feeding source or magma body

L = size of modelling area

T = temperature

Ψ = stream function

t = time

C = volumetrical heat capacity of saturated rocks

C_o = specific heat capacity of water

λ = coefficient of heat conductivity of saturated rocks

$V_x V_z$ = components of mass flow velocity

G = initial geothermic gradient

T_1 = temperature of magmas feeding the magma chamber

T_2 = initial temperature of the heat-feeding source (magma body)

ρ = density of water

L_m = specific heat of magma crystallization

C_m = specific heat capacity of magmas

t_1 = time for emergence of magma body

K = filtration coefficient

α = coefficient of thermal expansion of water

$\Psi_o(x)$ = stream function which defines the water exchange at the upper boundary of the modelling region

S = area of vertical section of the heat-feeding source

$Ra = kL\,\alpha T_2C_o/\lambda$ Rayleigh number

$Fo = t_1\lambda/CL^2$ Fourier number

$Fe = S/L^2$ Fedotov number

$In = \dfrac{C_o}{\lambda} \max\limits_{x_i,\, j \in 0,\, L} |\Psi_0(x_i) - \Psi_0(x_j)|$ Infiltration number

V = volume of magma chamber

Ω = volume of erupted volcanic rocks

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