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OB THE CONDITIONS OF WATER AND HEAT FEEDING 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 deptha of 300-800 m are 180-210°C. The natural discharge of the hydrothermal system includes the discharge of the Pauzhetka *springs* and a concealed discharge in the bed of the Pauzhetka River (95 kg/s) and the eteam discharge in the Kambalny Ridge (15 kg/s). Only the upper part of geothermal reservoir was penetrated by drillholes (up to 1200 m), therefore we have used a mathematical modelling to assess the conditions of water and heat feeding of the hydrothermal system. The hydrothermal system belongs to a linear fracturing zone of NW trend, therefore the two-dimensional model was used in our calculations, It has been defined that 1) The source of heating is a *magma* chamber located at a shallow depth, 2) The heat and mass transfer in the geothermal reservoir is defined by free and forced hydraulic convection, 3) The conductivity coefficient of a linear fracturing zone is 400-600 m^2/day, its width is 2 km and length is 10 km, 4) The water feeding is defined by infiltration in the recharge area.

Calculations of temperature and velocity fields agree with real data obtained in the Pauzhetka geothermal area, therefore they *may* be a base for assessment of water and heat feeding of the hydrothermal system. In accordance with these assessments, the main part of water resources is derived from infiltration. Heat feeding *may* be maintained by cooling of the magma chamber with a volume of 18 km^3 that is in accordance with the 'volume of Holocene igneous rocks.

EF FORMATION ON THE PAUZHETKA HYDROTHERMAL SYSTEM

The Pauzhetka hydrothermal system (Fig.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 NW direction 10 km long end 2 km wide. Structurally the hydrothermal system is confined to the fracturing zone of the NW trend 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 a 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 from the east with a few lakes lying at +100 - +200 m level. The intensity of water infiltration in the volcanic regions of Kamchatka is 10-20 kg/s km^2.

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 Drs. Sugrobov (1965, 1976), Voronkov (1983) and Kiryukhin (1984); the direct estimation of 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 130-150 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" reflecting lack of extensive 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 400-600 m^2/day.
(3) In the area 2x3 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 180-210°C, the thermal anomaly has a form 2 km wide elongated in the NW direction (parallel to homonymous tectonic fracturing).
(4) The coefficient of thermal conductivity of rocks composing the hydrothermal system for the upper part of reservoir is $2\text{-}5 \cdot 10^{-3}$ cal/cm s °C.

THERMAL HYDRODYNAMIC MODEL

In order to assess the conditions of the formation of water and heat feeding of the Pauzhetka hydrothermal system the numerical thermal hydrodynamic model was used. Its characteristics is given below (Fig.2):
(1) The model is two-dimenqional, taking into consideration that the hydrothermal system is confined to a linear zone of tectonic fracturing of the NW trend.
(2) The water and rocks are supposed to be in the state of thermal equilibrium.
(3) Fluid filtration is supposed to be one-phasal, because the hydrostatic pressure at deptha of 3-5 km (where the most considerable temperature fluctuations are possible) exoeeds the critical steam pressure, 225 bar.

(4) The filtration is taken to be stationary at each time step.
(5) Coefficients of heat conductivity, heat capacity, filtration and thermal expansion of water are taken to be constant, independent on temperature and pressure.
(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 the most considerable temperature fluctuations.
(8) The cooling magma chamber is taken to be a source of heat feeding of 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 baaed on the volume of Dikiy Greben volcano (30 km^3). After Fedotov (1980) the size of a magma chamber is connected with the volume of the corresponding volcano by relation expressing the heat balance between the energy spent for melting of ambient rocks and the amount of heat in magmas feeding the chamber. In order to average the parameter values thie connection may be expressed as

$$V = \frac{C_M(T_2 - T_1)}{C_M T_2 + L}\Omega \simeq 0.25\Omega \quad (1)$$

Kirsanova and Melekestsev (1984) consider, based on paleovolcanic reconstructions, that the proportionality coefficient between the volume of shallow chambers and corresponding volcanoes for long-existing volcanic centers is higher.

$$V = 2 \div 4\,\Omega \quad (2)$$

For the two-dimensional model formulas (1-2) are transformed (in this case the *magma* chamber or the heat feeding source is schematized as a rectangle):

$$S = (x_2 - x_1)\cdot(z_2 - z_1) \simeq 0.5\text{-}2.5\,\Omega \quad (3)$$

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

$$c\frac{\partial T}{\partial t} = \lambda\frac{\partial^2 T}{\partial x^2} + \lambda\frac{\partial^2 T}{\partial z^2} - C_0 V_x \frac{\partial T}{\partial x} - C_0 V_z \frac{\partial T}{\partial z} \quad (4)$$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} = -K\rho_0 \alpha \frac{\partial T}{\partial x} \quad (5)$$

$$V_x = -\frac{\partial \psi}{\partial z} \qquad V_z = \frac{\partial \psi}{\partial x} \quad (6)$$

The boundary conditiona may be defined as

$$\psi\Big|_{x=L,\,x=0,\,z=L} = 0 \qquad \psi\Big|_{z=0} = \psi_0(x) \quad (7)$$

where function $\psi_0(x)$ reflects the above-described conditions of water feeding of the hydrothermal system, $\max \psi_0(x)$ is the total value of infiltration feeding; $\frac{2}{1}\max \psi_0(x)$ is its average value in the recharge zone. The boundary temperature conditions are expressed as

$$T\Big|_{z=0} = 0 \quad T\Big|_{x=0,\,x=L} = G\cdot z \quad T\Big|_{z=L} = G\cdot L \quad (8)$$

The initial temperature conditions are expressed as

$$T\Big|_{t=0,\,x,z\bar{\in}[x_1,x_2][z_1,z_2]} = G\cdot z \qquad T\Big|_{t=0,\,x,z\in[x_1,x_2][z_1,z_2]} = T_2 \quad (9)$$

From equation *(5)* it follows that the initial conditions for stream function are unanimously defined by initial temperature distribution. The system of equations (4-9) was solved by the finite-difference method on digital computer EC 1033. The algorithm of digital solution consists in the following: (a) $\psi_1(x,z)$ was derived from equation (5) with zero right-hand side and boundary conditions (7) by the iteration method on the basis of the finite-difference scheme of longitudinal-transverse directions. The stream function obtained at this step characterizes, apparently, the infiltration regime which was in the system before the emergence of heat source ($t < 0$, forced convection).

(b) $\psi_2(x,z)$ was derived from equation (5) with zero boundary conditions with regard for the heat source existence. The obvious fact consisting in that the solution of elliptic equation with the right-hand side is a superposition of logarithmic type potentials was used. The obtained $\psi_2(x,z)$ characterizes the free convection regime.

(c) $\psi_1(x,z)$ and $\psi_2(x,z)$ are summarized, in order to obtain the initial stream function distribution (when $t=0$) for combined convections. This superposition is derived from the linear type of differential operator in the left-hand side of equation (5).

(d) The velocity field is calculated from equation (6).

(e) The temperature field for the first time step is calculated using the velocity field from equation (4) by the finite-difference method with the help of a scheme of longitudinal-transverse directions.

(f) The operation of the second step(б) is repeated, i.e. stream function is derived from the temperature field, etc.

The numerical algorithm was tested by comparison with data obtained by other authors (Garg and Kassoy, 1981). The numerical parameter values used in one variant of modelling in dimensions ha-

$C_0=0.3$ cal/g °C	$z_2=6$ km
$\lambda=6\cdot10^{-3}$ cal/cm s °C	$S=9$ km^2
$\kappa L=400$ m^2/day	$Fe=0.09$
$\alpha=10^{-3}$ °C^{-1}	$T_2=1000$°C
$\rho_0=1$ g/cm^3	$t_1=6000$ yr
$C=0.6$ cal/cm^3°C	$Fo=2\cdot10^{-5}$
$Ra=2000$	$\psi_0(x)=3.2\cdot x\cdot(x-10)$ kg/s·km
$L=10$ km	$\max\frac{2\psi_0(x)}{L}=15$ kg/s·km^2
$x_1=3.5$ km	$G=0.03$°C/m
$x_2=6.5$ km	$In=0.02$
$z_1=3$ km	

RESULTS OF CALCULATIONS; DISCUSSION

The results of calculations may be expressed as a succession of temperature and hydrodynamic fields referred to different periods of time which have passed from the moment of the origin of magma body (Fig.3). Now we shall consider this succession. Before the emergence of magma body ($t < 0$) the temperature increased linearly with depth in accordance with gradient G (Fig.3.1). The groundwater flow conditions in the considered permeable zone are defined by recharge in the right side (which imitates the eastern slope of the Kambalny Ridge and adjacent regions from the east) and by discharge in the left side (which imitates the valley of the Pauzhetka River) (Fig.3.2). Then the "instantaneous" emergence of magma body occurs (Fig. 3.3). This is reflected in e new structure of groundwater flows owing to free convection (Fig.3.4). Two thousand years after the emergence of the heat source the amplitude of free convection attenuates because of magma body cooling; the role of forced convection increases (Fig.3.6); the temperature anomaly arises slowly (pig. 35). The most recent of the thermo-hydrodynamic fields (Fig.3.7,8), which refers to time $t=6000$ years corres - ponds in time to those thermohydrodynamic conditions which 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 (Fig.3.9). The initial size **of** *magma* chamber (heat source), **S**, was used as a calibration parameter. The best *ag*reement between the calculated and actual temperature fields (the coincidence of 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 specific heat of water, C_0, upon the temperature (the 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 $\frac{\partial T}{\partial z}$ 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 the forcedconvection **is** dominated.

If the width of hydrothermal flow is taken to be 2 km, then its discharge equal to 150 kg/s will provide the **na**tural discharge of the hydrothermal system. **This** gives one more argument for the validity of this model. Thus, this model provides a thermohydrodynamic picture (Fig.3.8,9) of heat end 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 thermo-hydrodynamic 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 heat source imitating the *magma* chamber which emerged 6000 years *ago* at a depth of **3-6** 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 *ag*rees **well** with the volume of volcanic rocks erupted in Holocene. The water feeding of 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 specific heat of water upon the temperature; and steam effects in the upper part of reservoir.

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Nomenclature

x, z space co-ordinates
x_1, x_2, z_1, z_2 co-ordinates defining the location of heat feeding source or ma-

gma body

- L size of modelling area
- T temperature
- ψ stream function
- t time
- C volumetrical heat capacity of saturated rocks
- C_0 specific heat capacity of water
  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 of emergence of magma body
- K filtration coefficient
- α coefficient of thermal expansion of water
- $\psi_0(x)$ 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

$Ra = KL\alpha T_2 C_0/\lambda$ Rayleigh number

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

$Fe = S/L^2$ Fedotov number

$In = (KL)^{-1}\cdot \max_{x_i \in (c,L)} |\psi_0(x_i)-\psi_0(x_j)|$ Infiltration number

- V volume of magma chamber
- Ω volume of erupted volcanic rocks

REFERENCES

Cheng,P. and Lau,K.H., 1974. Steady state free convection in an unconfined geothermal reservoir. J.Geophys. Res., v.79, No.29, p.4425-4433.

Fedotov,S.A., 1980. On entrance temperatures of magma, formation, dimensions and evolution of magma chambers of volcanoes. Volcanol.Seismol.,No.4, p.3-30 (in Russian).

Garg,S.K. and Kassoy,D.K., 1981. Convective heat and mass transfer in hydrothermal systems. In: Geothermal Systems: Principles and Case Histories. Perg.Press, p.37-68.

Kirsanova,T.P. and Melekestsev,I.V., 1984. On the origin and age of the Khodutkinskie thermal waters. Volcanol.Seismol., No.5, p.49-60 (in Russian).

Kiryukhin,A.V., 1984a. The basis of calculated filtration scheme of the Pauzhetka geothermal deposit. Volcanol.Seismol., No.2, p.75-83 (in Russian).

Kiryukhin,A.V., 1984b. Thermal hydrodynamic model: hydrothermal system-shallow magma chamber. Volcanol.Seismol., No.3, p.25-35 (in Russian).

Sugrobov,V.M., 1976. Geothermal energy resources of Kamchatka and future prospects for their utilization. In: Hydrothermal Systems and Thermal Fields of Kamchatka, Vladivostok,p.267-280 (in Russian).

The long-existed center of endogenic activity in South Kamchatka. 1980, Moscow, Nauka, 170 pp. (in Russian).

Voronkov,V.A., 1983. On the schematization of hydrogeological conditions of the Pauzhetka geothermal deposit. Volcanol. Seismol., No. 5, p.39-49 (in Russian).

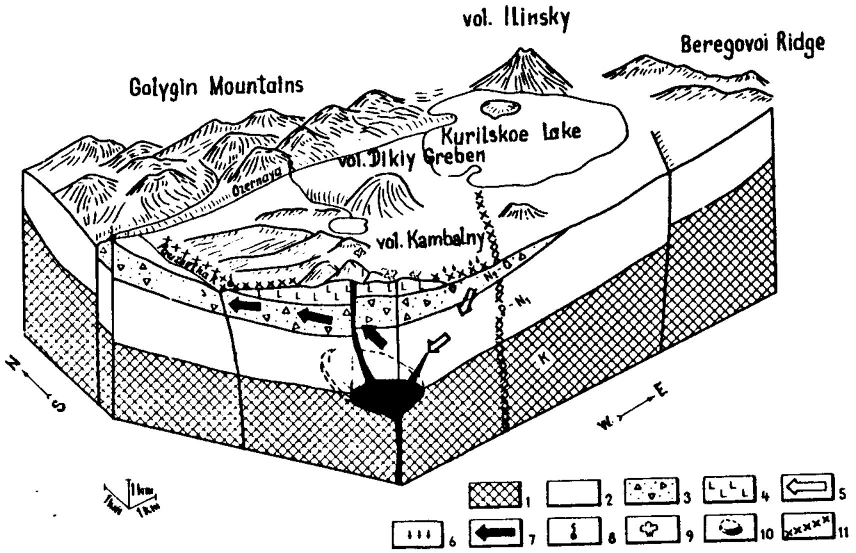

Fig.1. Block-scheme of the geological structure of the Pauzhetka hydrothermal system. Geological structure: 1=Cretaceous metamorphosed rocks; 2=Paleogene-Neogene volcanogenous-sedimentary rocks formed predominantly in marine conditions; 3=volcanogenous-sedimentary rocks of Pliocene-Quaternary age with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

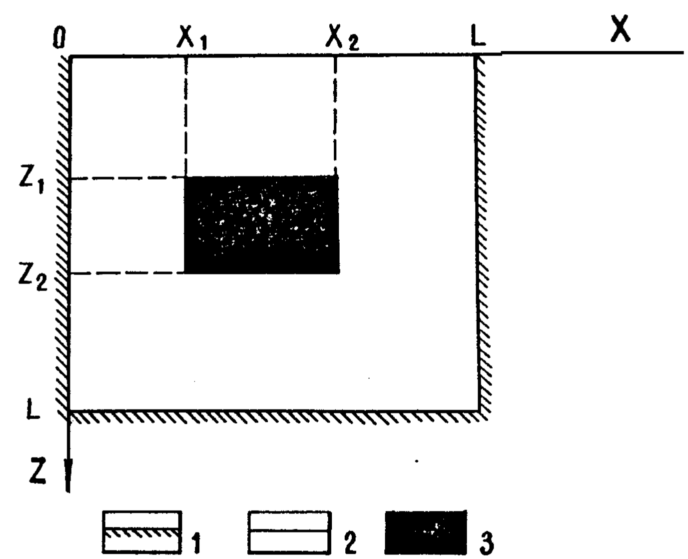

Fig.2. Schematization of thermal hydrodynamic conditions of the Pauzhetka hydrothermal system. 1=hydraulically impermeable boundaries; 2=hydraulically permeable boundaries at which water exchange with surface waters occurs; 3=source of heat feeding.

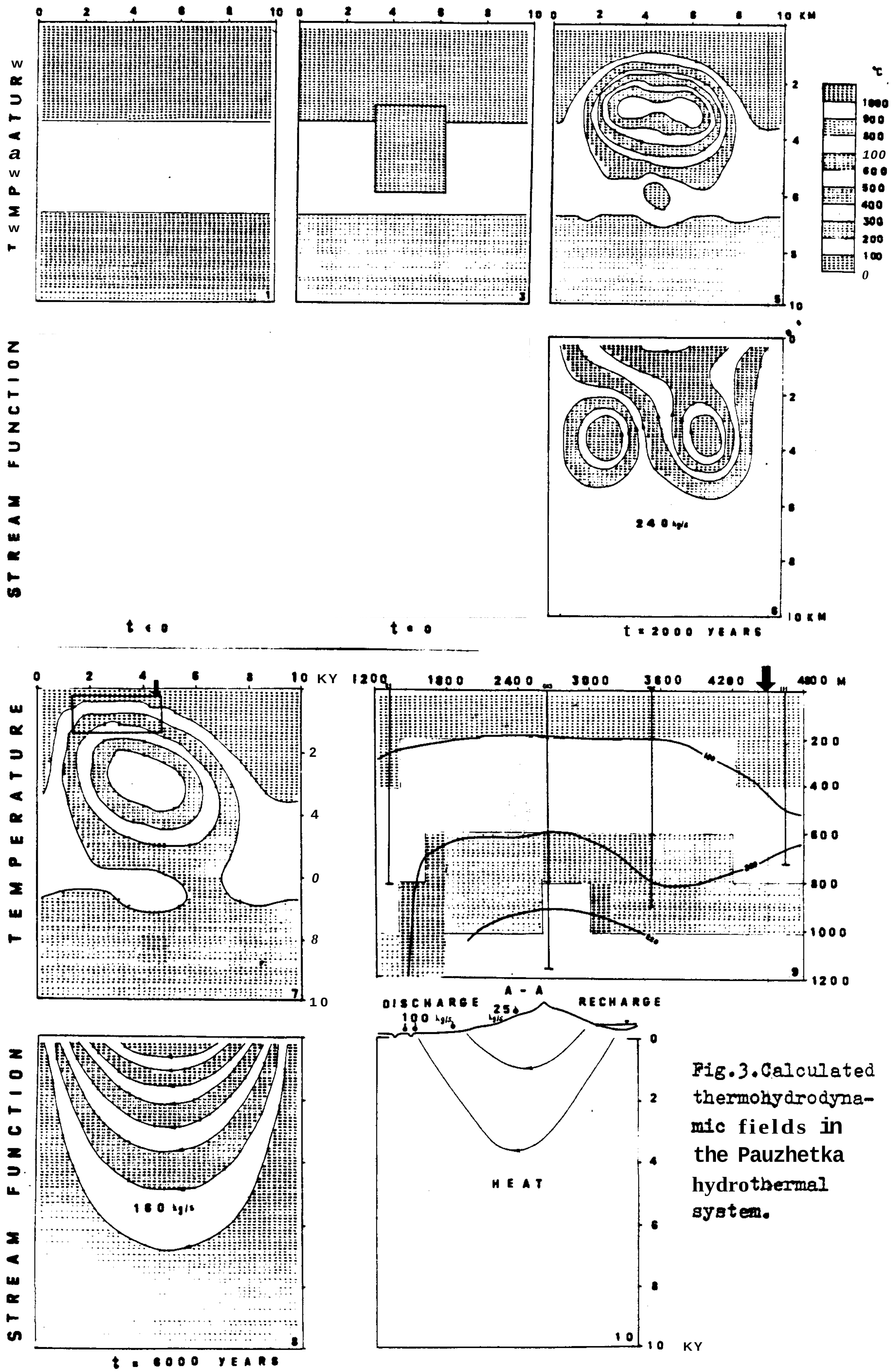

Fig.3.Calculated thermohydrodynamic fields in the Pauzhetka hydrothermal system.