Change in the Heat Regime of the Pauzhetka Geothermal System in Kamchatka As a Result of Exploitation

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ABSTRACT

The Pauzhetka geothermal system is located in a volcano-tectonic depression near the active volcano Kambalny.

Temperatures at depths of 300-800 m are 180°-210°C. The exploitation of productive horizons with a withdrawal of 130-160 kg/s commenced in 1966.

A noticeable lowering of the enthalpy in the wells was observed during the exploitation period. Analysis of temperature and pressure variations in the reservoir using heat-mass transfer equations gives an estimation of the heat and water resources supplied from the interior of the system to the area under exploitation. The value of the water resources supplied from the depth is 85 kg/s on the average, the rest of the water being supplied from the peripheral colder parts of the reservoir.

These estimates lead to the conclusion that the utilization of hydrothermal systems associated with active volcanoes is accompanied by recoverability of cold water from the surrounding rocks that may influence substantially their heat regime.

INTRODUCTION

The Pauzhetka geothermal system is located in a volcano-tectonic depression in southern Kamchatka (Fig. 1). The first exploration wells were drilled in 1957 and the Pauzhetka geothermal power station began to operate with the capacity of 5 MW at the end of 1966. Fifteen years of industrial exploitation of the Pauzhetka geothermal area have produced rather substantial changes in the heat regime of the area (Fig. 2). The conditions under which the system is exploited were analysed in order to assess the water and heat flows into the system within the time interval 1966-1980 and to forecast the heat regime in the subsequent period of exploitation.

RESERVOIR DATA AND MODELLING ASSUMPTIONS

The hydrogeological and geothermal conditions of the exploitation area can be schematized as follows:

i) All the production wells in the calculation scheme of heat transfer in the productive layer are considered as one « large well » operating with a water discharge equal to the total discharge of the production wells. This « large well » is located in the centre of the water extraction area (Fig. 3).

ii) Geofiltrational parameters of the productive layer are averaged from sectors radiating from the centre of the « large well » by assuming that the velocity of filtration within each sector depends only upon the distance to the centre of the « large well ». Four sectors have been distinguished: northern, western, southwestern and southeastern.

iii) The upper productive layer is composed of psephitic and psammitic tuffs of the Pauzhetka suite (SUGROBOV, 1965). Sugrobov's data indicate that the thickness of the productive layer, M,

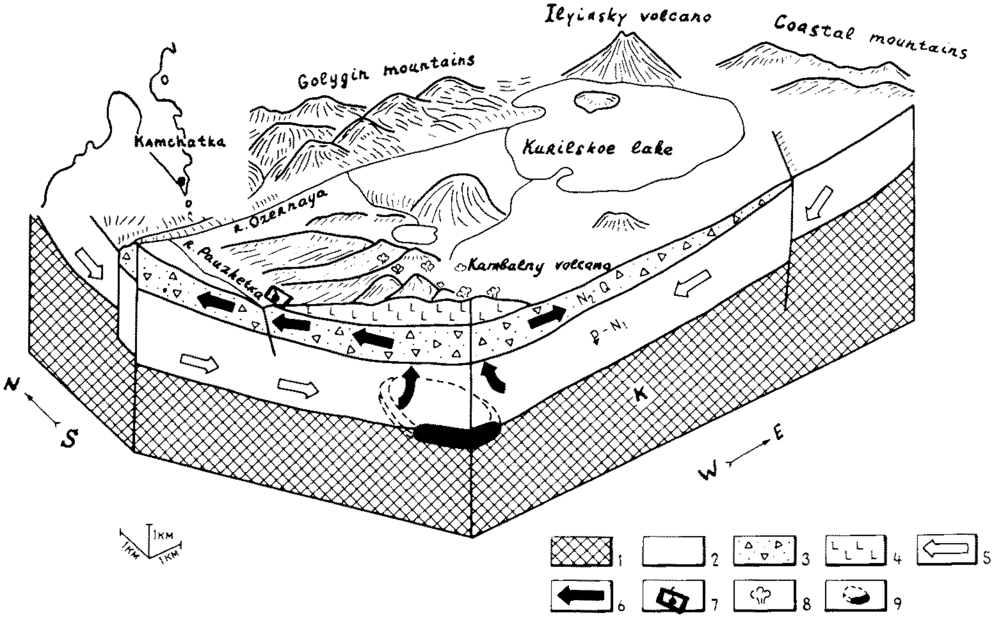

FIG. 1 – Location map of the Pauzhetka geothermal field in a volcano-tectonic depression of southern Kamchatka. 1 - Relatively impermeable basement (Cretaceous, K); 2 - more permeable sandstones of Eocene-Miocene age (P-N_1); 3 - permeable tuffs of the Pauzhetka suite (Pliocene-Quaternary, N_2-Q); 4 - relatively impermeable lavas (Quaternary, Q_2-Q_4); 5 - direction of flow of cold waters; 6 - direction of flow of thermal waters; 7 - Pauzhetka thermal springs: the exploited area (see also Fig. 3); 8 - fumaroles; 9 - hypothetical magma chamber.

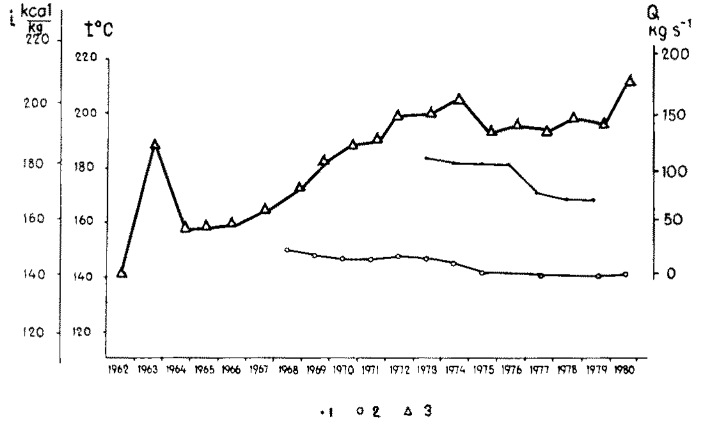

FIG. 2 – Heat regime of the exploited area in the period 1962-79. 1, Dots: change in the average yearly enthalpy of production wells during 1966-80; 2, Open circles: average yearly temperatures of monitor wells; 3, Triangles: withdrawal rates.

within the production sectors can be averaged to 90 m in the northern and western sectors, and to 80 m in the southeastern sector.

The coefficient of volume heat capacity of the productive layer, C, was assumed to be 0.6 cal/cm^3 °C (CATALDI and MUFFLER, 1977).

iv) The thickness of the upper relatively impermeable layer, m – composed of the aleuropelitic tuffs of the Pauzhetka suite – ranges from 120 to 200 m (SUGROBOV, 1965; Fig. 4). The average value of $m = 160$ m has been used in the calculations.

The coefficient of thermal conductivity, λ, according to SUGROBOV and KHATKEVICH (pers. comm., 1980), is 3.8×10^{-3} cal/cm·s °C.

The coefficient of heat capacity is the same as that of the productive layer, i.e. 0.6 cal/cm^3°C.

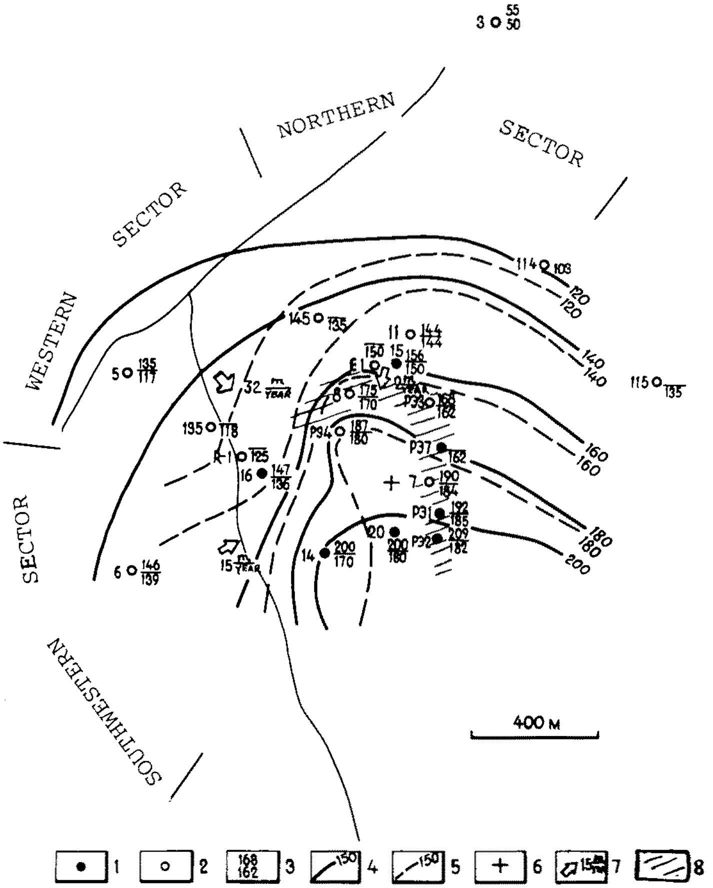

FIG. 3 – Hydrologic conditions of the exploited area (in plan). 1 - production wells; 2 - monitor wells; 3 - temperature in the upper productive layer in 1968-72 (upper number) and in 1978-80 (lower number); 4 - isotherms in the upper productive layer in 1968-72; 5 - isotherms in the upper productive layer in 1978-80; 6 - centre of the « large well »; 7 - velocity of the isotherm shift, m/yr; 8 - area of water leakage from the alluvial deposits to the productive layer.

v) The thickness of the lower relatively impermeable layer within the production area is 200 ÷ 300 m. This layer separates the first from the second productive layer which are connected with one another by fractures.

vi) The temperature of the water, T, in the productive layer is taken as the average value for the overall thickness of the productive layer, or as the temperature corresponding to the enthalpy, i, of the production well if this well is cased down to the bottom of the impermeable layer. Under this condition, « temperature in the layer » and « enthalpy of the production well » are assumed to be identical.

vii) The conductive heat flow through the bottom of the reservoir as compared to the heat flow through the roof can be neglected by taking into account that the temperature gradient in the deposit decreases strongly with depth. The conductive heat flow within the upper impermeable layer is considered to be quasi-stationary – except for the central sites where seepage of groundwaters may occur.

viii) The vertical convective heat flows into the external parts of the upper productive layer have been neglected because these flows are supposed to be present only in the central part of the area where the pressure depletion induced by exploitation is more significant, and because seepage of ground and deep waters may locally occur through tectonic fractures (Fig. 4).

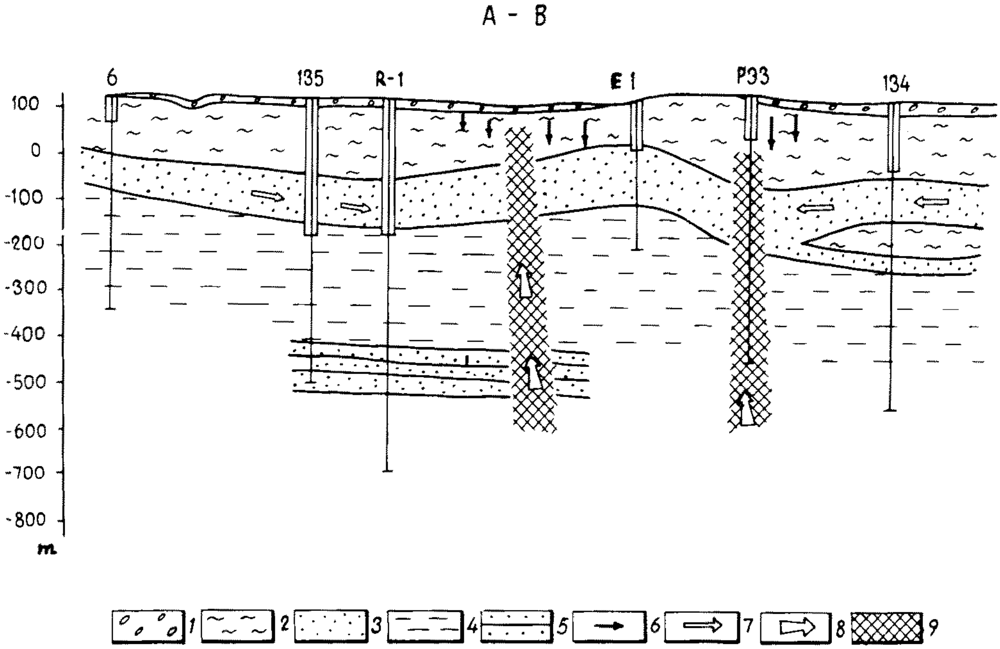

FIG. 4 – Hydrogeology of the exploited area (in section). Horizontal and vertical scales are equal. 1 - alluvial deposits; 2 - upper relatively impermeable layer; 3 - upper productive layer; 4 - lower relatively impermeable layer; 5 - lower productive layer; 6 - water resources from the alluvial deposits; 7 - water resources supplied owing to elastic storage in the upper productive layer; 8 - water resources supplied from the depth; 9 - zone of local tectonic fracturing.

WATER FLOW CONDITIONS IN THE EXPLOITATION AREA

In order to make a quantitative analysis of the water flow conditions, the resources (Q) are assumed to include: *i*) resources supplied from the depth through zones of tectonic fracturing (Q_d); *ii*) resources supplied owing to reworking of elastic storage in the upper productive layer (Q_{el}); and *iii*) resources supplied from the alluvial deposits (Q_{al}) (Fig. 4).

Assessment of Resources Supplied Owing to Reworking of Elastic Storage of the Productive Layer (Q_{el})

The equation of heat transfer to the external parts of the productive layer – taking into account the local hydrogeological and hydrogeothermal conditions – is:

$$MC\frac{\partial T}{\partial t}+\frac{Q_{el}}{2\pi r}C_o\rho_o\frac{T}{r}+\lambda\frac{\partial T}{\partial m}=0 \tag{1}$$

with initial temperature distribution

$$T\Big|_{t=0}=T_o(r) \tag{2}$$

In (1) C_o is the heat capacity of waters; ρ_o is the water density; r is the distance from the centre of the «large well» The first term of eq. (1) expresses the change in enthalpy in an elementary volume of productive layer because of convective heat transfers (second term) and heat losses through the roof (third term). The initial temperature distribution $T_o(r)$ is assumed to be stationary because of a re-establishment of the natural geotemperature regime which was disturbed by experiments in 1962-63 and reset in 1966.

The nondimensional expression of eq. (1) and (2) is:

$$T+\frac{\beta}{\bar{r}}\frac{\partial T}{\partial \bar{r}}+\gamma\frac{\partial T}{\partial \bar{r}}=0 \tag{3}$$

$$T(0,\ \bar{r})=\mathrm{T}_o(\bar{r}) \tag{4}$$

where

$$\beta=\frac{m\ Q_{el}C_o\rho_o}{2\pi\lambda M^2} \tag{5}$$

$$\gamma=\frac{CMm}{\lambda t_o} \tag{6}$$

$$\bar{t}=t/t_o\quad \bar{r}=r/M \tag{7}$$

The solution of (3) and (4) is:

$$T=T_o\ \left(\sqrt{\bar{r}^2+\frac{2\beta}{\gamma}\bar{t}\ }\right)\cdot \mathrm{e}\ {-t/\gamma} \tag{8}$$

Inasmuch as the average γ value in the exploited area is 0.7×10^3, $e^{-t/\gamma}$ can be neglected

$$T = T_o \left(\sqrt{\bar{r}^2 + \frac{2\beta}{\gamma} t} \right) \tag{9}$$

where

$$\frac{\beta}{\gamma} = \frac{C_o \rho_o}{c} \cdot \frac{t_o}{2\pi M^3} \cdot Q_{el} \tag{10}$$

From eq. (9) and (10) it can be seen that during exploitation the shift in the isotherms (change in the temperature distribution) relative to the centre of the «large well» occurs at the velocity

$$V = \frac{\beta}{\gamma \bar{r}} = \frac{C_o \rho_o}{c} \cdot \frac{t_o}{2\pi M^3 \bar{r}} \cdot Q_{el} \tag{11}$$

And *vice versa*, if the shift velocity is known the resources supplied by elastic reserves, Q_{el} can be estimated by:

$$Q_{el} = \frac{C}{C_o \rho_o} \cdot \frac{2\pi M^3 \bar{r}}{t_o} \cdot V \tag{12}$$

If Q_{el} is estimated for a single sector, then the radius of the sector must be used instead of 2π.

If the value of V given in Fig. 3 is used, eq. (12) gives the following values of Q_{el}:

Southwestern sector: 13.4 kg/s
Western sector : 20.0 kg/s
Northern sector : 6.4 kg/s

The total amount of peripheral waters from these sectors is 39.8 kg/s.

Assessment of Resources Supplied from the Alluvial Deposits (Q_{al})

In the valleys of the rivers Pauzhetka and Bystry (Fig. 3) cold groundwaters flow into the impermeable layer because levels in the productive layer have been lowered so much as to make the infiltration of such waters feasible. The cooling of the upper impermeable layer as shown by the thermograms of monitor wells (7, 8 and E-1) testifies that this process occurs (Fig. 5). Where monitor wells R-1 and 11 are located (Fig. 3) the infiltration of groundwaters through the impermeable layer does not occur as shown by the thermograms

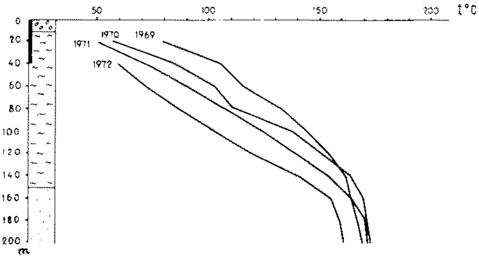

FIG. 5 – Temperatures measured in monitor well 8 between 1969 and 1972.

character. Thus, the area where this infiltration occurs is limited and of the order of 110,000 m^2.

The velocity of leakage can be estimated by using the equation of heat balance in the impermeable layer for the time $t_1 - t_o$:

$$\int_{t_o}^{t_1} q_{\text{cond}}(t)\mathrm{d}t - V_{\text{al}}\Delta t C_o \rho_o (T_1 - T_o) = \int_0^m C[T(t_1,\ Z) - T(t_o,\ Z)]\mathrm{d}Z \qquad (13)$$

$\int_{t_o}^{t_1} q_{\text{cond}}(t)\mathrm{d}t$ is the inflow of conductive heat to the impermeable layer from a reservoir where the temperature is kept constant because of hot water infiltrations. If the temperature in the impermeable layer is decreased (instantaneously) by a factor ΔT, the total supply of conductive heat from the reservoir at time «t» will be (KARLSLOW and EGER, 1974):

$$2\lambda \Delta T \sqrt{\frac{tC}{\pi\lambda}} \qquad (14)$$

The second term in eq. (13) is the amount of heat spent for heating the overflowing water and the right-hand side of the equation shows the change in enthalpy for the whole impermeable layer.

In equations (13) and (14) giving the velocity of leakage, T_1 is the temperature in the reservoir, T_o is the ambient temperature of groundwaters (10°C), ΔT is half of the change in temperature of the upper impermeable layer for the time considered in the calculations (Fig. 5).

Calculations have shown that the leakage velocity V_{al} is equal to 3.2×10^{-8}m/s. Hence, if the leakage area is known, the average withdrawal of the groundwaters supply from the alluvial deposits is:

$$Q_{\text{al}} = 110{,}000\ \text{m}^2 \times 3.2 \times 10^{-8}\ \text{m/s} \times 10^3\ \text{kg/m}^3 = 3.5\ \text{kg/s} \qquad (15)$$

Assessment of the Water Supply from the Depth

In our scheme of water feeding, with the term of «deep water» we mean the water supply from the southeastern sector encompassing the most heated near-surface sites of the Pauzhetka geothermal system, as well as the water supply from lower horizons saturated with hot waters through zones of tectonic disturbance. In predicting the heat regime these waters have been considered together and the name of «deep waters» was given to them because their enthalpy will hardly change at the «reasonable» time of exploitation, as it will be said hereafter.

The average productivity of water in 1972-1979 was 130 kg/s; taking into account the values of Q_{el} and Q_{al} previously obtained and the relation:

$$Q = Q_{\text{el}} + Q_{\text{d}} + Q_{\text{al}}$$

we get $Q_{\text{d}} = 85$ kg/s.

THE HEAT REGIME OF THE AREA UNDER EXPLOITATION

The heat regime can be assessed on the basis of changes in time of the average enthalpy for all the production wells. It is evident that:

$$i = \frac{Q_{\text{el}}}{Q}\, i_{\text{el}} + \frac{Q_{\text{d}}}{Q}\, i_{\text{d}} + \frac{Q_{\text{al}}}{Q}\, i_{\text{al}} \qquad (17)$$

Using the Q_{el}, Q_{d} and Q_{al} values obtained and assuming that $Q_{\text{el}} : Q_{\text{d}} : Q_{\text{al}}$ is constant, we obtain

$$i = 0.31\, i_{\text{el}} + 0.65\, i_{\text{d}} + 0.03\, i_{\text{al}}$$

It is assumed that $i_{\text{d}} = \text{Const} = i/_{t=0}$, that is that the enthalpy of the hot waters supplied from the interior of the hydrothermal system to the production wells remains invariable in the whole course of exploitation, and that it may be defined as the average enthalpy at the beginning of exploitation. For the considered wells i_d is equal to 182.5 kcal/kg. The constant value of the temperature of hot waters in the system may be explained by the long existence of the Pauzhetka geothermal field.

Routine observations of monitor wells 7 and 8 (Fig. 5) have shown that the temperature of infiltration water is 160°- 170°C which results from the mutual compensation of the cooling effect of seepage and the increasing conductive heat flow from below. If we consider the small contribution of i_{al} to i (eq. 18), we obtain an error not greater than 0.15% for $i_{al} = 165$ kcal/kg.

i_{el} is the average of i_{el}^{k} of sectors, where k is the sector index:

$$i_{el} = \sum_{k=1}^{1} \frac{Q_{el}^{k}}{Q} i_{el}^{k} \qquad (19)$$

where i_{el}^{k} is determined from eq. (8) when $\bar{r} = 1.5$ (which is the mean distance of the productive wells from the centre of the « large well »). Results of calculations from eq. (18) and (19) are shown in Fig. 6 which gives a prediction of heat regime for all the production wells if the pattern of the water resources exploitation remains the same as that in 1979.

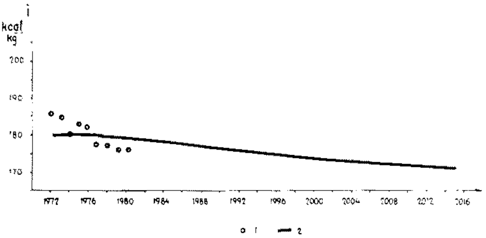

FIG. 6 – Heat regime of the wells of the Pauzhetka geothermal area. Open circles, 1: changes in the average enthalpy of production wells during exploitation; Solid line, 2: theoretical enthalpy changes.

CONCLUSIONS

1. The study of the water feeding conditions of the exploited area of the Pauzhetka geothermal system has shown that 66% of the water has a « deep » origin, 31% is supplied from the peripheral sites of the first productive layer (due to the reworking of elastic reserves), and 3% is given by the infiltration of groundwaters into the upper impermeable layer.
2. A model of heat regime in the area was derived from the schematization of the hydrogeological conditions and of water flow into the exploited area. This model allows the prediction of changes in the average enthalpy of wells that for 50 years of exploitation the decline will be of 9 kcal/kg if the water discharge pattern does not vary.
3. The obtained assessment of heat regime indicates that high-temperature geothermal fields similar to Pauzhetka are reliable sources for geothermoelectrical energy production.

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