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THREE-DIMENSIONAL TEMPERATURE FIELD RECONSTRUCTION IN GEOTHERMAL RESERVOIRS BASED ON THE SPLINE APPROXIMATION OF GREEN'S FORMULA

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ABSTRACT

The basic idea of the method of three-dimensional temperature field reconstruction is to express the observable temperature field as a superposition of source functions and a core of "Δ^2"-operator (background temperature plane) in accordance with Green's formula. The technical realization of this method was provided on the basis of computer program LIDA-3 (Library of Data Approximation). It has been demonstrated that the method of three-dimensional temperature field reconstruction can be applied to convective geothermal reservoirs. The reconstruction of three-dimensional temperature fields of the Mutnovsky geothermal reservoir is shown as an example.

INTRODUCTION

The three-dimensional temperature field reconstruction based on the temperature logging data is of practical importance for
(a) establishing the temperature anomaly geometry and its genesis;
(b) assessing the heat energy storage (exploitational reserves of geothermal fields);
(c) determining the most favourable sites for geothermal drill holes;
(d) forecasting temperatures at different depths and in adjacent areas;
(e) identifying the high-temperature flows.

Until nowadays the temperature field reconstruction has been made "by hand" in vertical or horizontal (two-dimensional) cross sections on the basis of linear interpolation (extrapolation) taking into account the intuitive notions of an investigator. The attempt to solve reverse boundary problems for elliptic type equation is also inefficient because of the lack of real physical conditions for boundary conditions and geometry determinations. Therefore it is necessary to improve our methods of temperature field reconstruction to satisfy some energetic principles in a three-dimensional field.

METHOD OF TEMPERATURE FIELD RECONSTRUCTION

The stationary temperature field in convective geothermal reservoirs satisfies heat and mass transfer equations

$$\lambda \Delta T - C_0 V \nabla T = 0 \tag{1}$$

where T is the temperature; λ, the heat conductivity coefficient, C_0, the specific heat capacity of fluid; V, the mass filtration velocity; Δ, Laplas operator and ∇, nabla operator. The mass filtration velocity distribution V depends mainly on geometry of permeable channels in geothermal reservoirs. Then the second term in equation (1) expressed with the help of the heat source function f(x,y,z) can be rewritten as

$$\lambda \Delta T + f(x,y,z) = 0 \tag{2}$$

Equation (2) can be solved by finding the unknown sources f(x,y,z) in the three-dimensional field. However, the Green's functions for harmonic operator are not continuous. Therefore we transform equation (2) to biharmonic view by applying Δ-operator

$$\Delta^2 T + \Delta f = 0 \tag{3}$$

Thus, the problem of three-dimensional temperature field reconstruction can be reduced to selection of the Green's functions (sources) for biharmonic operator which can be expressed as

$$T(x,y,z) = \mu_0 + \mu_1 x + \mu_2 y + \mu_3 z + \int_\Omega \Delta f(x,y,z) \cdot \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2}\, dx_1 dy_1 dz_1 \tag{4}$$

where the first four right-hand terms are the core of "Δ^2" (Δ) operator and the last term is the source function (the Green's function). When the character of heat transfer is quasistationary, the approach based on formula (4) seems to be also possible; in this case the nonstationary term is also taken into account in function $f(x,y,z)$. It follows also from equation (4) that the temperature field reconstruction is made based on the piece-linear functions for which the mean square error of approximation is $0(h^2)$, where h is the distance between observational points. If the temperature data "T_i" in N points $(x_i y_i z_i)$ of the geothermal field are known, the Green's function which provides the observable temperature field can be expressed as

$$\sum_{i=1}^{N} \lambda_i \sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2} \qquad (5)$$

where λ_i is the intensity of sources (of convective nature, in our case) in points (x_i, y_i, z_i) which provide the achievement of "T_i" in observational points. The coefficients $\lambda_i (i=1,N)$ and $\mu_j (j=0.3)$ can be determined from a system of equations

$$\begin{pmatrix} T \\ 0 \end{pmatrix} = \begin{pmatrix} A & B \\ B^T & 0 \end{pmatrix} \begin{pmatrix} \lambda \\ \mu \end{pmatrix} \qquad (6)$$

where $T=(T_1 \ldots T_N)^T$, $\lambda=(\lambda_1 \ldots \lambda_N)^T$, $\mu=(\mu_0,\mu_1,\mu_2,\mu_3)^T$. A is the symmetrical matrix with N*N dimension and components $((x_i-x_j)^2+(y_i-y_j)^2+(z_i-z_j)^2)^{1/2}$, B- matrix with N*4 dimension, which consists of $(1,x_i,y_i,z_i)$ vectors; T is the sign of transpose of a matrix (vector). The last four equations in system (6) indicate that the background temperature plane $\mu_0+\mu_1 x+\mu_2 y+\mu_3 z$ is the average in terms of energy and balances positive and negative anomalies of the temperature field.

After the λ and μ determination, the three-dimensional temperature field reconstruction is realized by basis functions (4) using the coefficients λ and μ

$$T=\mu_0+\mu_1 x+\mu_2 y+\mu_3 z + \sum_{i=1}^{N} \lambda_i \sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2} \qquad (7)$$

In reality, temperature logging in boreholes is made with some error "δ"

$$\delta=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(T-T_i)^2} \qquad (8)$$

In order to assess this error in a system of equations (6) it is necessary to disturb somewhat matrix A

$$A \rightarrow A+\alpha E \qquad (9)$$

Then the contrasting effect of sources and sinks is decreasing. As a result, reconstructions based on formula (7) give an imitation of deviation from erroneous data owing to greater smoothing of the sought temperature field. The problem of searching for the spline functions to equation (6) taking into account equation (8) is solved by using "LIDA-3" computer program (Vasilenko,1987).

THREE-DIMENSIONAL TEMPERATURE FIELD RECONSTRUCTION OF THE MUTNOVSKY GEOTHERMAL RESERVOIR

Data base. The following data were used as a data base for temperature field reconstruction:
(1) bottom hole temperature logging data during drilling after several days of temperature build-up;
(2) data from flow tests (enthalpy, discharge) after penetrating the productive zone.

RESULTS OF CALCULATIONS AND THEIR DISCUSSION

The data base is in accordance with the state as of April 1988; the three-dimensional temperature field reconstructions were made for volume ($x\in 0,4000$ m, $y\in 2500, 6750$ m, $z\in -1300, +400$ m); the horizontal coordinates were arbitrary. The mean square deviation of the calculated temperature field from the actual data was 2°C (AL=1.0). Figures 1,2 and 3 show the temperature distribution in lateral (z=0m a.s.l.)(Fig.1), meridional (Fig.2) and latitudinal (Fig.3) sections. In the lateral section the main thermal anomaly has a center near well B-1 (the whole area of this anomaly is approximately 4 km², the temperature above 200°C). The temperature anomaly here has sharp boundaries with high temperature gradients in the west, north and south which point to the presence of hydrodynamically impermeable boundaries. In the north-east the temperature gradients are very low and the temperature field is more homogeneous which apparently point to large horizontal spread of thermal water flows in this direction.

In the meridional section (Fig.2) there is a prominent ascending flow in the region of well 01, which rises at an angle of 30-45° from the south. There is a descending fluid flow between wells 24 and 012 (descending at an angle of 45° to the south). Apparently, those are elements of semiconfined convective mesh. A subvertical steam tube feeding the natural steam jets (Dachnye fumaroles) is shot off from the upper part of the ascending fluid flow.

In the latitudinal section (Fig.3) the ascending flow can be identified by relatively symmetrical temperature anomaly in a section between wells 7 and 10. The forecasted maximum temperature in the area of the temperature field reconstruction, 200 m to the south of well 01 at an elevation of -1300 m, was 320°C. This flow is probably confined to the superposed submeridional fracture zone and contacts with Miocene intrusions.

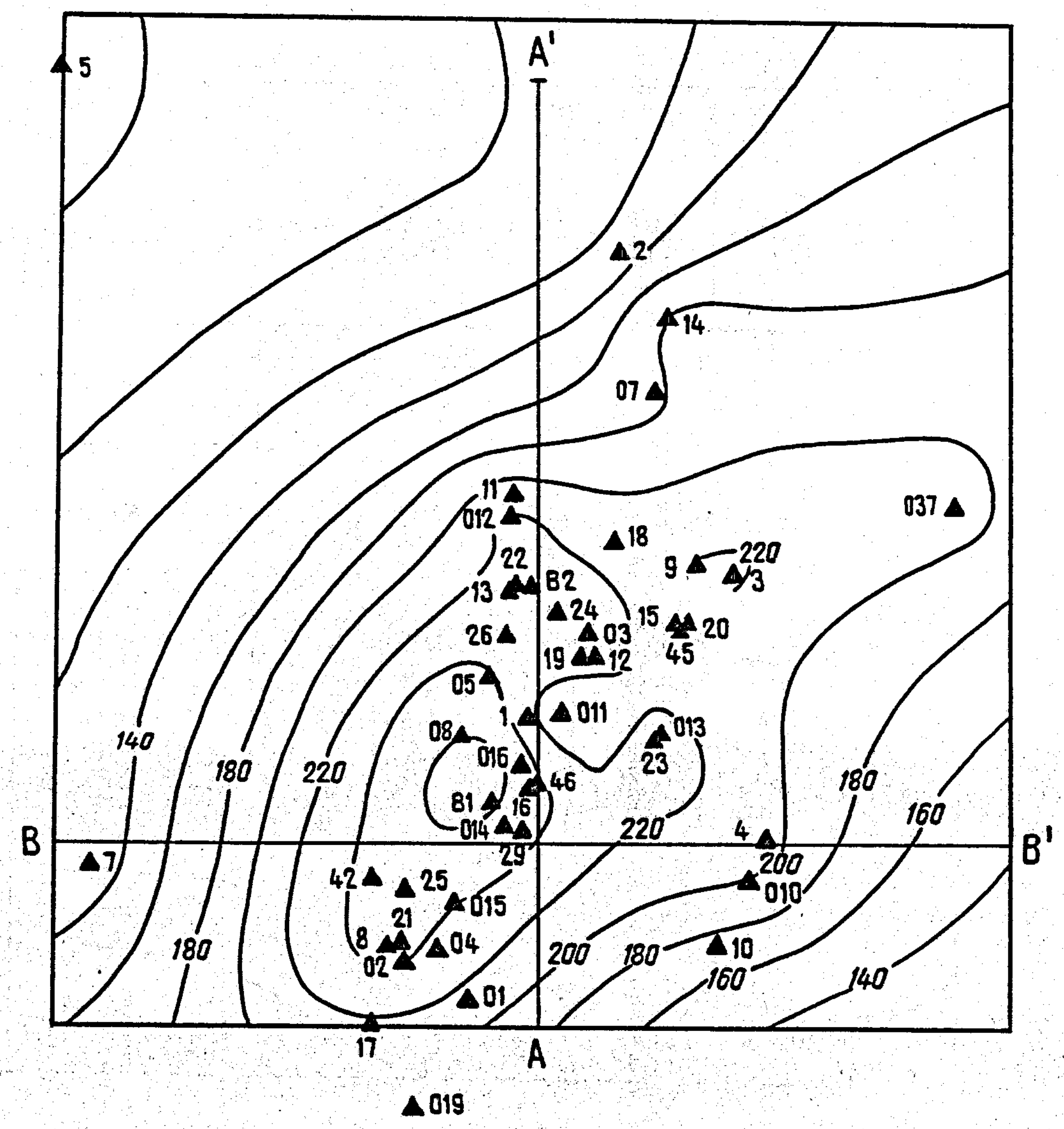
Analysis of the temperature field distribution in other sections also shows the existence of ascending hot water flow in the region of well 013; this flow rises at an angle of 75-80° from the east and it is also confined to the fracture zone of submeridional trend. A descending hot and cold water flow is present in the region of well 011-012 (it descends at an angle of ~45° to the south). This flow is confined to the fracture zone of north-west trend. Unfortunately, the volume of the paper does not allow us to present all corresponding sections of the temperature field.

CONCLUSIONS

The new method of three-dimensional temperature field reconstruction in geothermal reservoirs was suggested. This method is based on the spline approximation of the unknown field using Green's formula.

The three-dimensional temperature field reconstruction was made within the Mutnovsky

Fig.1. The temperature distribution within the Mutnovsky geothermal reservoir as a result of three-dimensional temperature field reconstruction in the lateral section, z=0 m a.s.l., scale 1:25000.



geothermal reservoir (Dachnye Site). The high-temperature flows were identified on the basis of temperature distribution. The forecasted maximum temperature at an elevation of -1300 m was 320°C.

The suggested method of temperature field reconstruction can also be applied to geothermal reservoir monitoring for the purpose of its exploration and exploitation.

REFERENCE

Vasilenko, V.A. (ed.) (1987), "Library of Data Approximation: Functions and Numerical Signal and Image Filtration", Part 1, Novosibirsk, 169 pp. (in Russian).

Fig.2. The temperature distribution within the Mutnovsky geothermal reservoir as a result of three-dimensional temperature field reconstruction in the meridional section AA', scale 1:25000 (horizontal), 1:10000 (vertical).

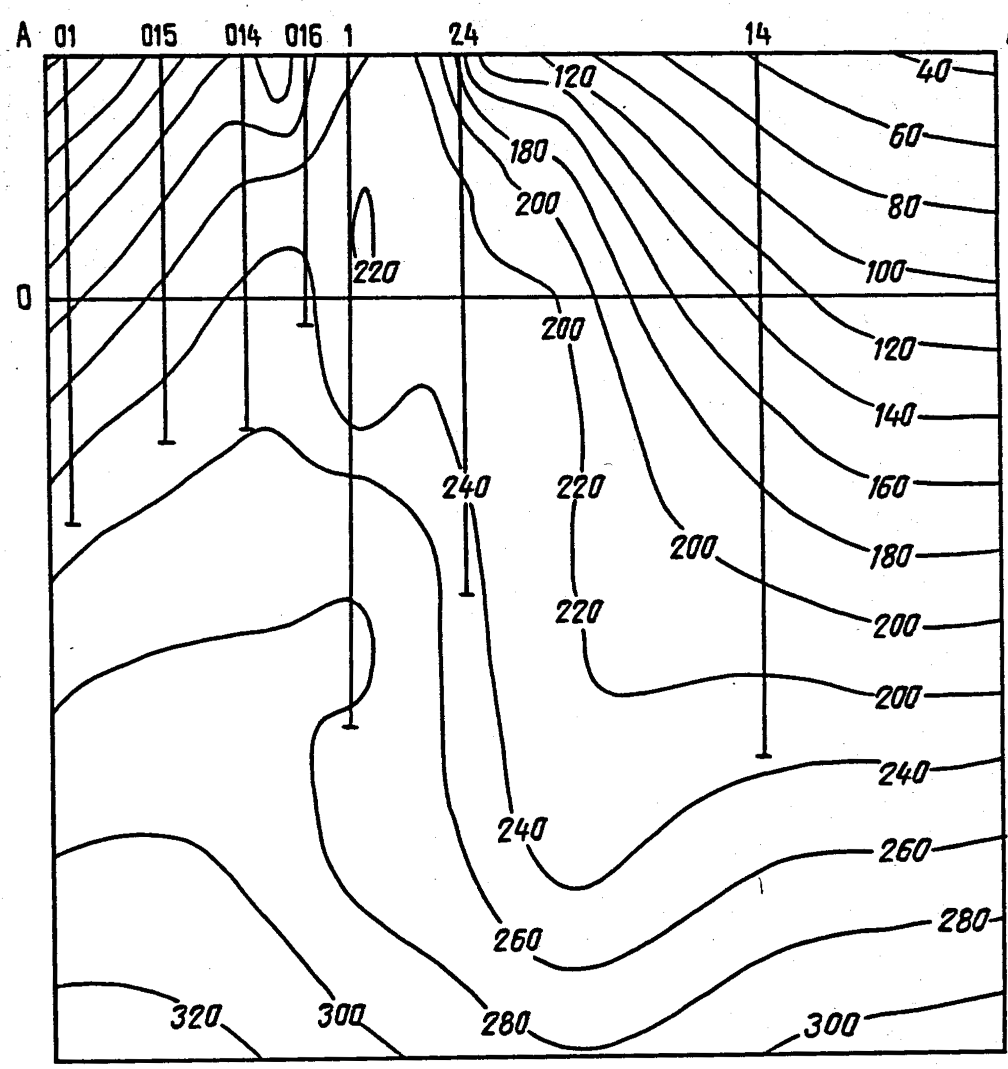


Fig.3. The temperature distribution within the Mutnovsky geothermal reservoir as a result of three-dimensional temperature field reconstruction in the latitudinal section BB[1], scale 1:25000 (horizontal); 1:10000 (vertical).