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VELOCITIES OF CONVECTIVE ASCENDING FLOW IN LIQUID-DOMINATED HYDROTHERMAL CONVECTION SYSTEMS

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ABSTRACT

Velocities of convective ascending flow in hydrothermal convection systems show typical characteristics. From simple one-dimensional analyses based on static temperature logging data, it was found that the macro velocities of convective ascending flow in active convection systems approach to given order of value. It may be closely related to the structure of permeability and consequently to the stress condition partially. Simulation studies for liquid-dominated hydrothermal systems were also conducted in order to clarify the effects of the permeability or the stress condition on the velocities of ascending flow.

INTRODUCTION

Convective ascending flow is an important phenomenon for understanding hydrothermal convection system and therefore for geothermal development. Hydrothermal convection systems have one or more domains of convective ascending flow. In this study, based on static temperature logging data from several geothermal areas, simple one-dimensional analysis for estimating the velocities of ascending flow in active convection systems is employed. The results may be closely related to the structure of permeability and consequently to the stress condition.

Hydrothermal convection can be representative as fluid and heat flows in a porous medium heated from below. Simulation studies for liquid-dominated hydrothermal systems, therefore, were also conducted in order to clarify the effects of the permeability or the stress condition on the velocities of ascending flow in this study.

GOVERNING EQUATIONS

Simple governing equations for fluid flow and energy transport are used in this study. Since liquid-dominated hydrothermal systems in natural state before exploitation are treated here, it is assumed that the flow region is represented by a porous layer, the fluid is single-phase (only water), and mass and heat flow is under the steady state. Accordingly, mass, momentum and energy balance equations of mass and heat flow in a porous medium are as follows (e.g. Donaldson, 1962):

$$\nabla \cdot (r_f \boldsymbol{v}) = 0 \qquad (1)$$

$$\nabla p - r_f \boldsymbol{g} + \frac{m}{\boldsymbol{k}} \boldsymbol{v} = 0 \quad \text{(Darcy's equation)} \qquad (2)$$

$$c_{pf}\, r_f \boldsymbol{v} \cdot \nabla T = l_m \nabla^2 T \qquad (3)$$

where boldface type indicates a vector or a second-order tensor quantity. In the above equations, r_f, c_{pf} and m are the density, the specific heat and the dynamic viscosity of fluid, respectively. $\boldsymbol{v}$ is the Darcian velocity vector of fluid. $\boldsymbol{k}$ is the permeability tensor of the porous medium and l_m is the isotropic thermal conductivity of the saturated porous medium. $\boldsymbol{g}$ is the gravity vector. T is the equilibrium temperature of saturated porous medium and P is the pressure of saturating fluid.

ONE-DIMENSIONAL ANALYSIS FOR VERTICAL FLOW IN A POROUS LAYER

In liquid-dominated hydrothermal convection, preferred orientation of hot-water flow possibly appears. Dominant vertical ascending flow may exist in the layer just above heat source, such as magma intrusion. While, dominant descending water flow may also occur in the layer. In those cases, one-dimensional analysis of vertical flow can be useful to estimate the vertical flow velocity and the vertical permeability of the layer.

Reducing equation (3), we obtain the differential equation for steady one-dimensional flow of heat and fluid through saturated homogeneous porous media (Bredehoeft and Papadopulos, 1965):

$$\frac{\partial^2 T}{\partial z^2} - \frac{c_{pf}\, r_f\, v_z}{l_m}\frac{\partial T}{\partial z} = 0 \qquad (4)$$

where v_z is the component of velocity in the z (vertical) direction (positive downward). Solving equation (4) with the condition that $T = T_1$ at $z = z_1$ and $T = T_2$ at $z = z_2$ (z_1 and z_2 are arbitrary if their points are in the layer and $z_1 < z_2$), we can obtain the following equation:

$$\frac{T - T_1}{T_2 - T_1} = \frac{\exp\{a(z - z_1)\} - 1}{\exp\{a(z_2 - z_1)\} - 1} \qquad (5)$$

where $a = c_{pf}\, r_f\, v_z \,/\, l_m$. In this equation, if $T_1 = T_0$ at $z_1 = 0$ and $T_2 = T_L$ at $z_2 = L$ (the length of vertical section over which temperature measurements extend) then the solution obtained by Bredehoeft and Papadopulos (1965) appears.

Assuming steady ascending flow in a homogeneous half-infinite porous medium and the boundary conditions that $T = T_0$ at $z = 0$, and $\mathrm{d}T/\mathrm{d}z \to 0$ and $T \to T_r$ as $z \to \infty$ when solving equation (4), we can obtain the following equation (Turcotte and Schubert, 1982):

$$\frac{T_r - T}{T_r - T_0} = \exp(az) \qquad (6)$$

Though equation (6) is only available to ascending flow, equation (5) is applicable to not only ascending flow but also descending flow. Applications of equation (6) to temperature logging data appear in analyses of the Kakkonda field, Japan in Hanano (1998) and Kajiwara et al. (1993) and of the Mori field, Japan in Sakagawa et al. (1994). In those analyses, the linear relationship of z to $\log(Tr - T)$ in the equation is used.

An Application of the Analysis

Kato et al. (1996) investigated a several of temperature logging data obtained from geothermal areas mainly in Japan. An example of one-dimensional analysis for vertically ascending flow using equation (6) is shown below. The procedure of this method to estimate macroscopic ascending velocity and vertical permeability is stated in Hanano (1998).

Fig. 1 shows the temperature profile obtained from the Okuaizu area (Suda and Yano, 1991). In this figure, Solid line represents measured temperature showing convective ascending flow type . dashed line shows temperature calculated using the ascending velocity obtained in this calculation . Fig. 2 shows the result of application of this method to the temperature logging data shown in fig. 1. Linear regression line is fitted to the data. As a result, the vertical ascending velocity is 2.0×10^{-9} (m/s) and in this case the correlation coefficient, R, is 0.997 where l_m is 2.0 (W/mK), r_f is 891 (kg/m^3), and c_{pf} is 4.39×10^3 (J/kgK) at the intermediate depth.

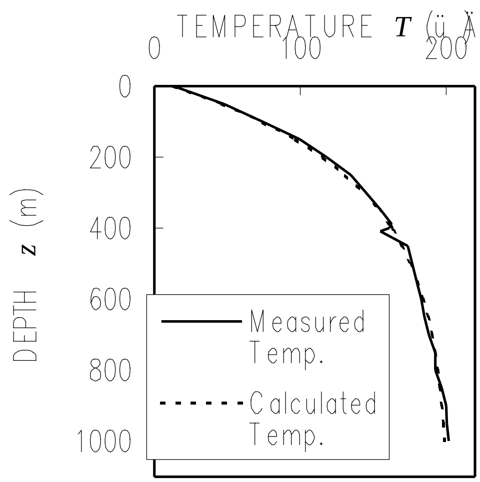

Fig. 1. *Temperature profiles at N58-OA-7 Well in the Okuaizu area. Solid line is measured temperature showing convective ascending flow type from Suda and Yano (1991) and dashed line shows temperature calculated using the ascending velocity obtained.*

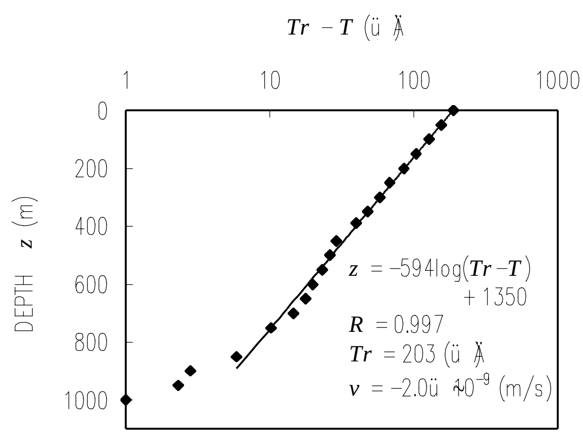

Fig. 2. *Fitting result to temperature data in figure 1.Solid line shows linear regression line of log(Tr - T) to z.*

Results of application of this method to more than ten areas show that the velocities of convective ascending flow in the upflow region of the convection have the same order of values, 10^{-9}. (Kato et al., in preparation). This velocity means approximately 3 cm per year. It may be interesting results for geophysicists and geothermal researchers.

TWO-DIMENSIONAL MODEL FOR LIQUID-DOMINATED HYDROTHERMAL CONVECTION SYSTEM

Galerkin finite element method is used in numerical simulation for understanding behavior of liquid-dominated hydrothermal convection system in two dimensions. The governing equations used here are shown in the previous section (equations (1) - (3)). These differential equations are transformed to simultaneous linear equations by employing the method and solved for pressure and temperature. Permeability in permeable region is assumed as isotropic and stress-dependent variable, that is equivalent to depth-dependent variable.

An example of models and results of 2-D simulation is illustrated in figs. 3-5. Here, the velocity of active ascending flow shows characteristices mentioned above.

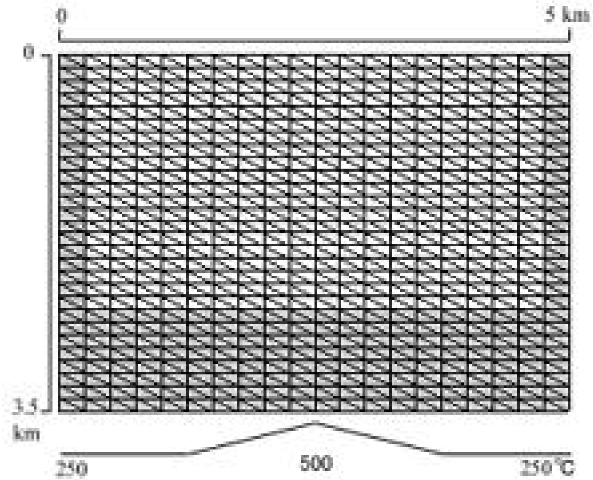

Fig. 3. Grid mesh and bottom boundary temperature distribution of 2-D simulation model. Permeability of gray area is 10^{-18} m^2 and that of white area is depth-dependent variable.

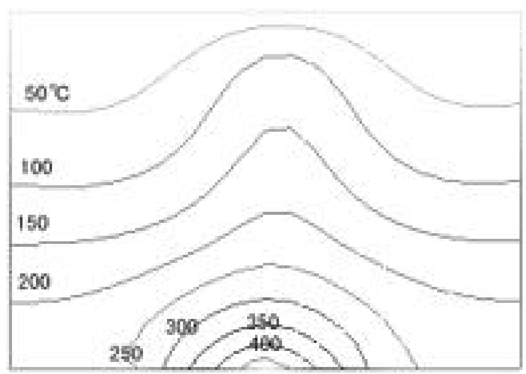

Fig. 4. Temperature distribution of the simulation results.

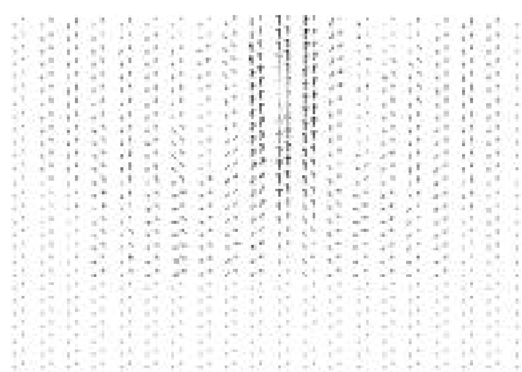

Fig. 5. Mass flow rate of the simulation result.

CONCLUDING REMARKS

In this study, simple one-dimensional analysis based on static temperature logging data and two-dimensional simulation studies for liquid -dominated hydrothermal systems were conducted in order to clarify the effects of the permeability or the stress condition on the velocities of ascending flow. Consequently, macro velocities of convective ascending flow in hydrothermal convection systems show typical characteristics. From simple analyses based on static temperature logging data, it was found that the velocities of ascending flow in active convection systems approach to given order of value. It may be closely related to the structure of permeability and accordingly to the stress condition partially.

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