THERMAL GROUNDWATER IN DEEP STRATIFIED RESERVOIRS IN OITA PREFECTURE, JAPAN

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Most of hot springs are commonly seen at valleys of rocks exposed or on fan deposits in mountaineous regions in Japan. They have been flowing out naturally from ancient times, accompanying occasionally with surface geothermal activities behind them, though hot waters nowadays are usually extracted by drilling and pumping out directly from shallow aquifers or fractured formations in their environs. Such hot waters have been frequently considered as a result of ascending of geothermal fluid from deep zones through faults or fractured systems, and subsequently sometimes spreading laterally into aquifers in shallower zones as the fluid being diluted.

In recent years, extractions of deep thermal water from thickly deposited strata have been increased in lower and flat regions such as plain and basin, where there have been no surface signs of hot springs. Though the underground temperature is not so high there, thermal waters extracted by drilling as deep as 700m to 1000m are made for many uses, such as bathing, domestic heating, hot water swimming pool and hothouse of glass culture, as the areas are urban regions in many cases.

Common features found through exploitaion of deep thermal waters in Oita prefecture are : (1) the underground temperature increases linearly with depth with the gradient of 5-7 deg per 100m depth, (2) the horizontal distribution of temperature is nearly uniform to a relatively wide extent, (3) the piezometric head of water is nearly uniform throughout the strata, (4) thermal waters of extremely different quality are stored within the strata, and (6) the change of chemical composition of water is abrupt spatially.

From these evidences, it seems that groundwater within the strata is essentially stagnant or a negligible rate of flow, and that the vertical heat flow must be dominated by conduction, owing to the horizontally stratified structure of formations. This is a clear contrast with the matter that the active geothermal phenomena are caused by convective heat transfer with upward flow of geothermal fluid through the vertical structures such as faults or fractures.

It is noted that the underground temperature distribution in this thickly stratified formations indicates the existance of faint bands accompanying with somewhat high temperatur. The temperature deviations range around 15 deg uniformly from shallow to deep zones. The location of high temperature bands coincides with that of the abrupt change of water quality. Therefore, the existance of faults is inferred along the high temperature bands, and the bands must be caused by the upward movement of groundwater from deep zones through fractures even in the stratified formations.

This paper concerns with the distribution of underground temperature from this point of view, that is, the effect of upward flow of deep thermal groundwater stored within stratified formations through a vertical fault. The difference and connection between the shallow hot waters in geothermal fields and the deep thermal waters in thickly stratified formations will be discussed.

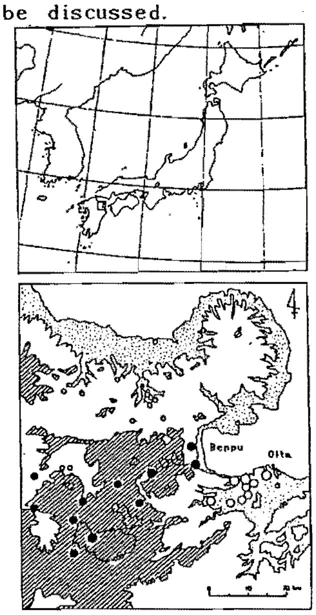

Fig. 1 Map of spas in Oita pref.

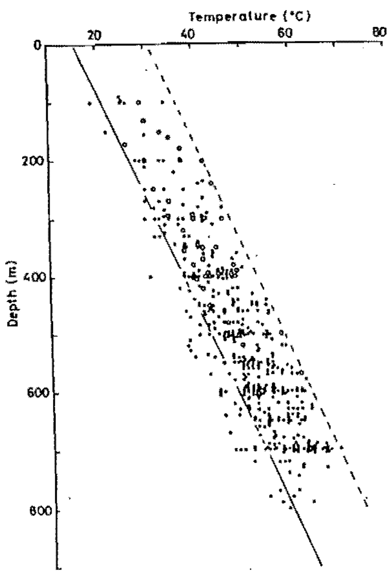

Fig. 2 Underground temperature (Oita plain)

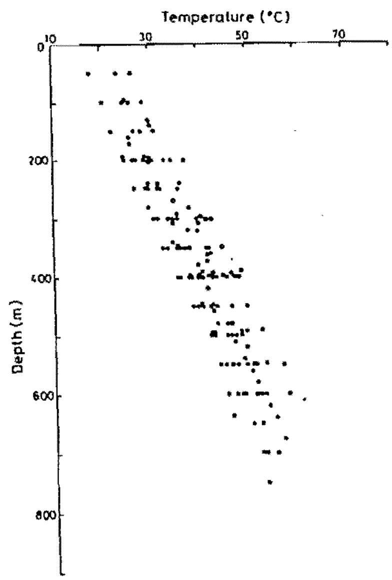

Fig. 3 Underground temperature (Northern area)

1. Some features in thickly stratified formations in Oita plain

Figure 1 shows the distribution of spas in Oita prefecture, Japan. Solid circles indicate the high temperature type, which are located mostly at relatively higher elevations. Open circles are the deep thermal water type, which are exploited in thick sedimentary formations in lower flat regions. In the scope of figure, the existance of the Beppu-Shimabara Graben is inferred with the trend of ENE-WSW direction. The spas of high temperature type situate around the central line of graben (Beppu hydrothermal area, which is the largest spa in this area, situates at the easternmost location in this graben), and almost all of the spas in the figure distribute within the graben.

Underground temperatures are usually measured at several depths of each borehole in the course of drilling. The accuracy of measurement is not so good under the influence of boring process, but the data would be available in such the situation that the ground temperature is not so high, permitting the accuracy to the range of about 5 ℃. Figure 2 shows the underground temperature against depth in the strata in Oita plain, in the southern side of Beppu spa. Figure 3 shows those in the northern side. It is noted that the situations of underground temperature are not so different with both the sides, that is, the thermal state is approximately same within the graben, except near the active geothermal areas and volcanoes.

In the Oita plain, many boreholes (over 110 holes) are drilled for deep thermal water and then many data have been accumulated with respect to underground temperature, water head and chemical composition of water in the sedimentary formations. The features are summerized as follows:

(1) The underground temperature of each hole is approximately linear with depth. Some of them show somewhat curving.

(2) Almost temperature/depth relationships are bounded clearly by two parallel straight lines as drawn in figure 2. The width of band is about 15 deg and the slope of lines is about 6 deg per 100m depth.

(3) The lower line is extrapolated at the ground surface into about 15 ℃ which is nearly equal to the annual mean of air temperature in the area, then the line may indicate the ground temperature as the background of stationary state controlled by conduction of heat flow.

(4) The higher part of temperature distrubutes horizontally forming high temperature bands which are more clearly observed periodically in deeper zones as shown in figure 4. Figure 5 is the distribution of water temperature flowing out at the ground surface from boreholes. The water temperature also forms the high temperature bands whose locations coincide with those of underground temperature. These bands run nearly parallel horizontally with each other and

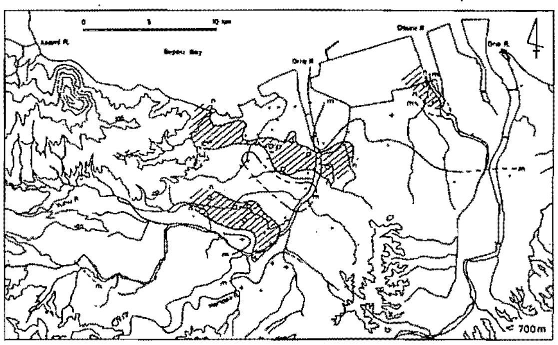

Fig. 4 Underground temperature at 700m depth (g : 54.5, m : 57.0, n : 63.0℃)

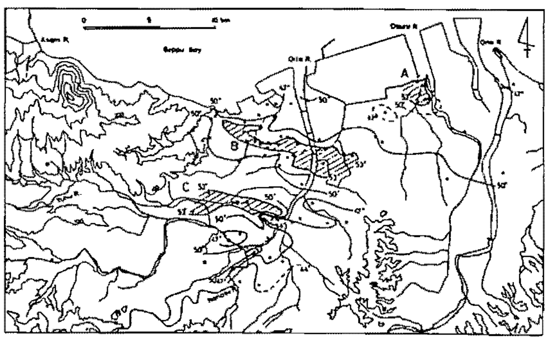

Fig. 5 Temperature of water pumped out at the surface

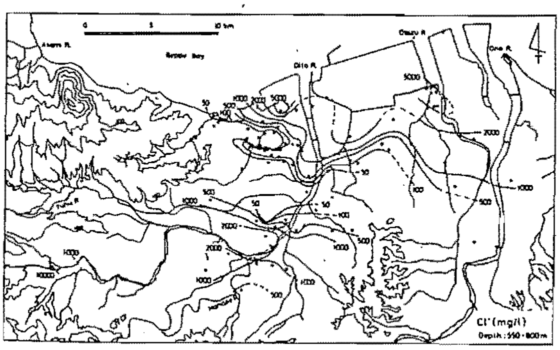

Fig. 6 Cl^-(ppm) in water from the depth 550 to 800m

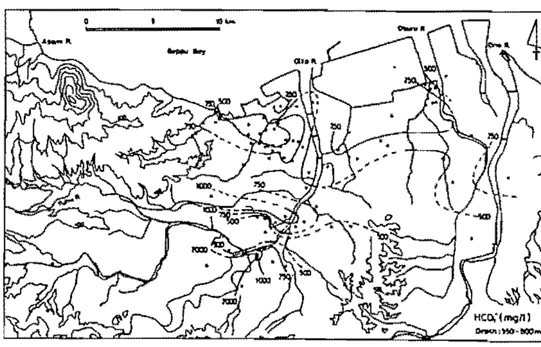

Fig. 7 HCO_3^-(ppm) in water from the depth 550 to 800m also parallel to the Asami Fault which plays a significant role in the southern part of Beppu hydrothermal field. Thus, the bands may be related to the structure acompanying with faults.

(5) The Cl^- and HCO_3^- concentrations in hot waters extracted through holes are changed steeply near the high temperature bands as shown in figure 6 and 7, respectively. This may indicate the vertical discrepancy of layered strata including the marine layers and limnetic ones separately.

(6) The piezometric head of water is approximately uniform within the range of 10m.

From these evidences, it can be considered that the high temperature bands may be owing to the effect of slow upward flow of groundwaters along faults from deeper zones.

2. Modeling of underground temperature in thickly stratified formations

As mentioned above, the existance of high temperature band can be supposed to indicate the upward flow of groundwater in thickly stratified formations through a fault or a fracture zone. So, we will consider the following simplified condition to construct a model (figure 8).

(1) The strata are horizontally layered. Then groundwater cannot move easily in the vertical direction, but can move in the horizontal one.

(2) A vertcal fracture zone (fault) limited in a narrow width runs through the stratified formation. Water can move vertically only along the fracture zone. The vertical transmissivity of the zone is assumed to be uniform in the mean sense along it.

(3) The piezometric head of groundwater is uniform throughout the strata except in the fracture zone.

(4) The horizontal seepage of groundwater in the strata toward the vertical fracture zone is assumed to be in the manner that the flow rate is in proportion to the head difference between the strata and the fracture zone at each depth. The seepage coefficient is also assumed to be uniform in the mean sense along the zone.

(5) The underground temperature θ_∞ in the strata is linear with depth:

$$\theta_\infty = \alpha + \beta z \tag{1}$$

where, z is measured positively downward from the upper edge of vertical fracture zone, at which water flowing upward in the fracture runs over spreading into a shallow aquifer.

Based on these assumptions, we will consider the upward flow Q of water within the fracture zone per unit width per unit time as in the form:

$$Q = K\frac{dh}{dz}, \tag{2}$$

where, h is the piezometric head in the fracture zone at the depth z, and K is the transmissivity of zone per unit horizontal width. The horizontal seepage flow q in the strata per unit vertical area per unit time toward the vertical fracture zone is assumed as:

$$q = b\,(H - h)\ , \tag{3}$$

where, H is the water head in the strata, and b is the seepage coefficient between the strata and the fracture zone.

The horizontal heat flux per unit time per unit vertical section in the strata to the vertical fracture zone expressed as $c\rho f$ (c and ρ : the specific heat and density of water) is given as:

$$f = \left(\theta q + 2\kappa\frac{\partial \theta}{\partial x}\right)_{x=0}, \tag{4}$$

where $\kappa = k/\rho c$ (k is the thermal conductivity of the strata) , x is the horizontal

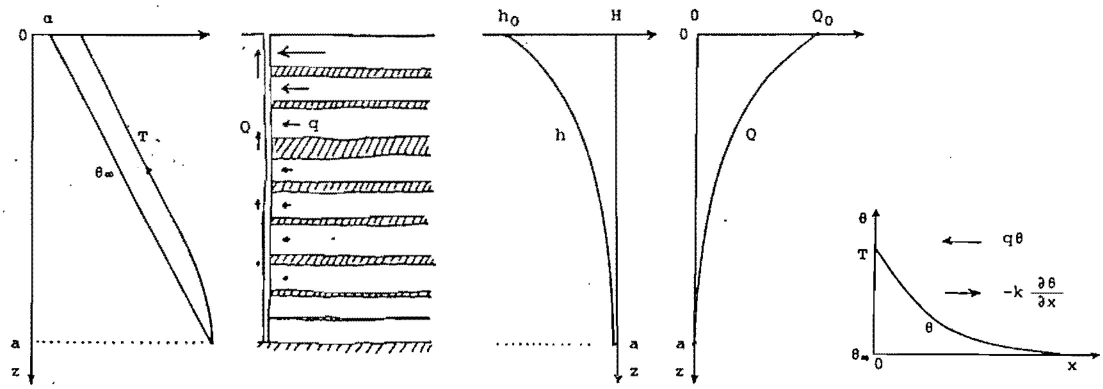

Fig. 8 Model of thickly layered formation accompanying with a fracture zone

distance from the fracture zone, and θ is the temperature at (x, z) in the strata.

Using the continuity equations for water and heat:

$$-\frac{dQ}{dz}=q \quad \text{and} \quad -\frac{d(QT)}{dz}=f, \tag{5}$$

the head h and temperature T in the fracture zone can be expressed as:

$$\frac{d^2h}{dz^2}+\frac{b}{K}(H-h)=0 \tag{6}$$

and

$$-Q\frac{dT}{dz}=\kappa\left(\frac{\partial\theta}{\partial x}\right)_{x=0}, \tag{7}$$

where, the vertical heat conduction is assumed to be small as compared with the convective transfer in the fracture zone. If the vertical conduction in the strata can be neglected as well, then the value in the parentheses in the right hand side of equation (4) becomes independent of x, and we obtain the simple equation of temperature in the fracture zone as:

$$\frac{dT}{dz}=\frac{q}{Q}(T-g), \tag{8}$$

For the case that no inflow from underlying basement exists, that is, the fracture zone is closed at the strata bottom locating at the depth of $z=a$, the integrations of equations (6) and (8) become:

$$H-h=(H-h_0)\cdot\cosh\{\mu(a-z)\}/\cosh(\mu a) \tag{9}$$

$$T=\theta_\infty+(\beta/\mu)\cdot\tanh\{\mu(a-z)/2\}, \tag{10}$$

respectively, where, $\mu=(b/K)^{1/2}$, and $h=h_0$ at $z=0$.

If the condition of $\mu(a-z)/2\ll 1$ is satisfied, then the temperature distribution of water ascending in the fracture zone becomes:

$$T=\theta_\infty+(\beta/\mu)=\alpha+(\beta/\mu)+\beta z. \tag{11}$$

This is the same representation as the result observed in thick sedimentary formations in the Oita plain, that is, the temperature of water ascending along the fault is parallel to that of the strata with respect to depth. Thus, the temperature difference between two parallel lines in figure 2 can be corresponded to the value of parameter β/μ. Based on the actual data that $T-\theta_\infty=15$ deg and $\beta=0.06$ deg$\cdot$m^{-1}, the value of μ is estimated at around 4×10^{-3} m^{-1}.

3. Discussion

We have considered the role of fracture zone on the underground temperature under an idealized condition and got the result favorable to the actual underground situation. Even if the fracture is opened to the underlying fractured basement, the effect of upward flow of geothermal fluid from the basement also can be obtained to be similar as that in the case of the closed condition mentioned above, as long as the rate of inflow of geothermal fluid is not so large and its temperature is not so high compared with that of strata at the bottom. At the present ranging up to 800m depth of data, it is considered that the effect of bottom condition does not appear clearly in the data within the range of depth as parallel nature of two lines in figure 2 conserves within the range. This implies that the location of bottom might be deeper than at least 2000m. The result does not contradict with the result of gravity data.

The model can include also the case that the water head in fracture at the bottom is higher than that of the strata, that is, high temperature water flows into the fracture in the strata from the basement. In the case, hot water layer is formed spreading laterally in the zone ranged in $h>H$, and the temperature T in the fracture is conserved within the zone. (In this case, however, the temperature of the horizontal layer might be lowered as far from the fault because of cooling effect.)

In concluding, the underground temperature is controlled by the hydraulic properties of fractured system and not influenced so seriously by the flow rate of water ascending along the fault under a given heat flow condition. That is, the parameter μ, the square root of ratio of horizontal/vertical reduced permeabilities of fractured system, plays a significant role in the underground temperature. In general, if rock formations are fractured vertically (poorly permeable horizontally), then the value of μ is to be small, then the temperature of ascending flow in the rock fractures can be high. This might be related closely to forming a geothermal area. On the other hand, in sedimental strata, the lateral permeability might play a role to make the value of μ large, then the temperature of water does not reach so high. Geothermal situations, thus, could be said to be controlled by the combination between horizontal and vertical structures of formations.