HYDROTHERMAL CONVECTION IN GEOTHERMAL RESERVOIRS WITH SLOPING BASEMENT AQUITARDS

YANO, Y., Geol. Surv. of Japan, Higashi 1-1-3, Tsukuba 305, Japan

1. INTRODUCTION

The flow of hot water in a geothermal reservoir with an inclined bottom has not been studied as extensively as the flat-bottom case. In many real fields, the rock formations comprising the reservoir basement are far from horizontal. Hydrothermal convection is generally confined to a permeable aquifer region lying below the watertable and above the basement, owing to the impermeable character of the latter. Thus, the geometry of the permeable zone may depart significantly from a rectangular vertical section. Most Japanese geothermal fields are located in volcanic areas; deep magma bodies supply heat conductively upward through irregular tilted basement structures to drive buoyant hydrothermal circulation systems in the overlying permeable strata. Under these circumstances, the effects of basement orientation may be of considerable importance.

This paper presents preliminary results of a theoretical study(involving numerical simulation techniques) of natural convection patterns in reservoirs with sloping lower boundaries. (Calculations involving non-horizontal basement layers are not unusual in simulation studies of particular geothermal fields, but the influence of bottom slope itself has not yet been systematically investigated in general fashion.) First, simple base cases are treated; these base cases are then perturbed in various ways to examine the influence of pertinent key parameters. The significance of the parameters must be established before applications to practical field situations should be undertaken.

2. SIMPLE MODELS

Figures 1 and 2 illustrate results for two elementary base cases, showing both stable mass flux and temperature distributions for the systems whose properties are listed in Table 1. A finite-element two-dimensional single-phase simulator(Yano,1987) was used. Stationary boundary conditions were imposed and unsteady calculations were carried out in time until an essentially steady state was reached: the reason that an unsteady method was used will become apparent below. In both cases, the upper constant-pressure surfaces were horizontal(no topographic effects), and the vertical side boundaries both represent planes of symmetry. In Figure 1, the temperature along the inclined basement surface was fixed, whereas in Figure 2 a uniform heat flux was imposed.

It is noteworthy that the resulting convective patterns are nearly the same. The temperature along the basement is almost uniform in the fixed-heat-flux case(Figure 2) except at the corners. The thermally-driven circulation creates a rapid upward flow pattern parallel to the basement surface, resulting in a nearly uniform temperature distribution there.

Since both the basement slope and the heat source mechanism in real geothermal fields are consequences of the geological history of the area, the two effects are interrelated in practice. For real systems, the situation is likely to depart from these simple models in a variety of ways. To evaluate such effects, additional calculations were undertaken.

3. EFFECTS OF KEY PARAMETERS

Table 2 lists a number of factors which influence numerical calculations of convective flow phenomena in aquifers with inclined basement boundaries. Here, the effects of those parameters which have been investigated so far are described.

Qualitative changes in flow pattern may result from changes in overall system geometry. The length, depth, and angle of inclination of the basement, together with the heating rate, in large measure determine the scale of size of the convection cells. For example, Figure 3 illustrates a case similar to that of Figure 2, except that the prescribed heat flux from the basement has been substantially increased. Owing to the change in Rayleigh number, the number of convection cells is greater in Figure 3.

Figure 4 illustrates a different situation. In this case, the system is isothermal. The flow is driven by topographic slope, with the water-table surface elevation to the left higher than to the right, inducing a net flow from left to right.

Combinations of different driving mechanisms result in increased flow complexity(Yusa,1983; Hanaoka,1986). Combining the fixed-temperature thermal convection mechanism of Figure 1 with the topographically-driven forced convection mechanism of Figure 4 results in the flow pattern illustrated in Figures 5.1-5.4. As discussed by Yano(1987), this combination of boundary conditions can sometimes create periodic oscillatory solutions under certain circumstances (as in this case). Despite the stationary boundary conditions, a steady solution is never reached - instead, the system will continue to oscillate indefinitely, as indicated. It should be noted that, in real geother-

GEOMETRY
width: 7 km
depth: 1500m(left edge), 5000m(right edge) for horizontal surface cases(figures 1, 2 and 3)
topography for figures 4-6: rising to the left with 1/50 slope(depth of left edge = 1640m)

ROCK PROPERTIES
permeability: 2 md
thermal conductivity: 0.005 cal/sec·cm·℃
porosity: 0.2
rock grain density: 2.7 g/cm^3
rock grain heat capacity: 0.23 cal/g·℃

BOUNDARY CONDITIONS AND SOURCES/SINKS
sides: symmetry(insulated for both heat and mass)
upper surface: temperature=10 ℃, pressure = 1 atm
bottom: figures 1 and 5: uniform temperature(200 ℃)
figures 2 and 6: uniform heat flux(3.5 HFU)
figure 3: uniform heat flux(5.8 HFU)
figure 4: uniform fixed temperature(10 ℃)

INITIAL CONDITIONS
hydrostatic pressure, uniform temperature at 10 ℃

Table 1 Parameters used for the numerical simulations depicted in figures 1 to 6.

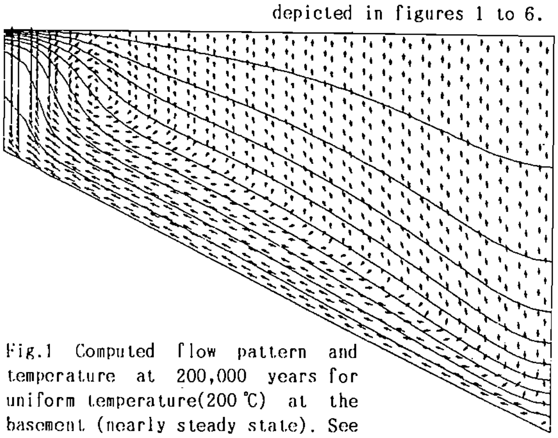

Fig.1 Computed flow pattern and temperature at 200,000 years for uniform temperature(200 ℃) at the basement (nearly steady state). See table 1 for the parameters for the calculation. Temperature contour interval is 20 ℃. Lengths of arrows are proportional to logarithm of mass flux density; scale varies from figure to figure.

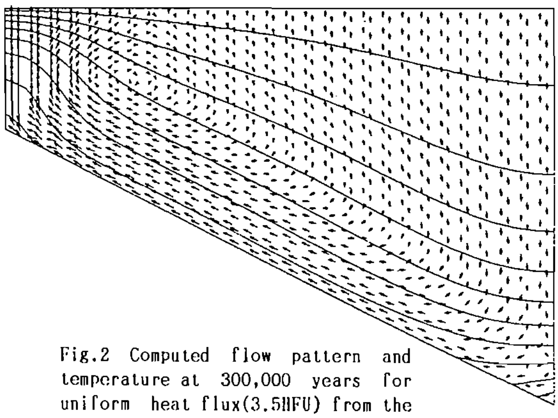

Fig.2 Computed flow pattern and temperature at 300,000 years for uniform heat flux(3.5HFU) from the basement(nearly steady state).

GEOMETRY
basement: length, depth, angle
surface topography
two- or three-dimensional

ROCK PROPERTIES
permeability: magnitude, anisotropy, heterogeneity(cap rock)
minor factors: thermal conductivity, porosity, heat capacity
rock type: porous medium or fractured rock

FLUID PROPERTIES
approximations used for water properties
salinity

HEAT SOURCES
type of boundary condition(heat flux, fixed temperature) and magnitude
spatial distribution of conductive input
hot water inflow from basement

TIME OF OBSERVATION
elapsed time since initial(cold) state
steady or oscillatory solution

COMPUTATIONAL FACTORS
accuracy of calculation, mesh size, time step

Table 2. Important factors influencing numerical simulation of convection above basement slopes.

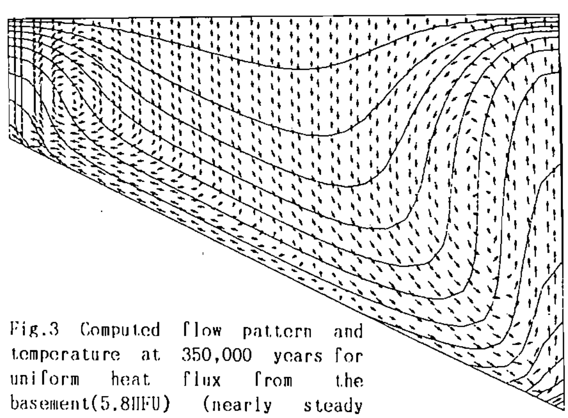

Fig.3 Computed flow pattern and temperature at 350,000 years for uniform heat flux from the basement(5.8HFU) (nearly steady state).

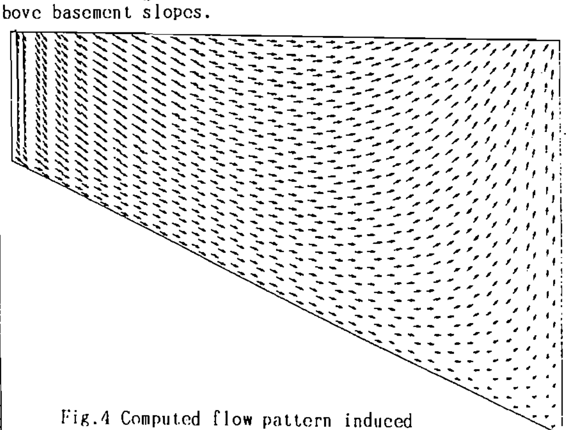

Fig.4 Computed flow pattern induced by topography without heat input.

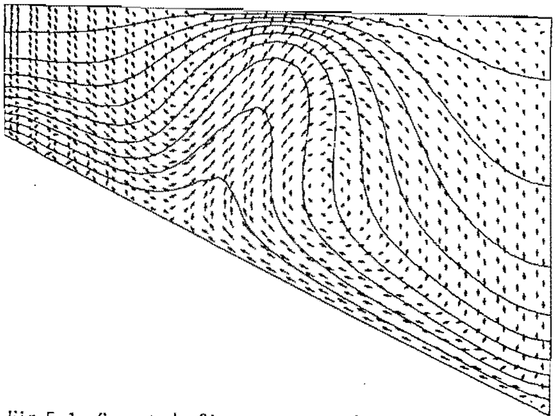

Fig.5.1 Computed flow pattern and temperature at 400,000 years with topographic effect added to the conditions of figure 1.

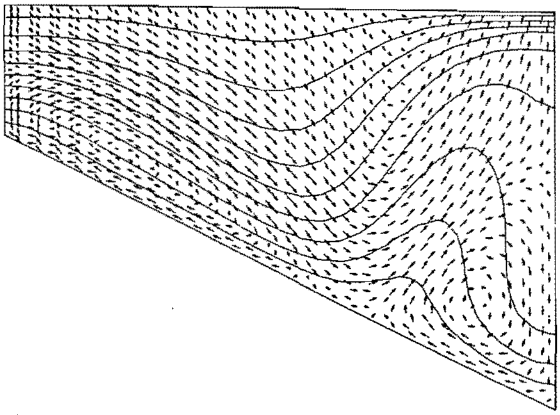

Fig.5.2 Computed flow pattern and temperature at 500,000 years for the same conditions as figure.5.1.

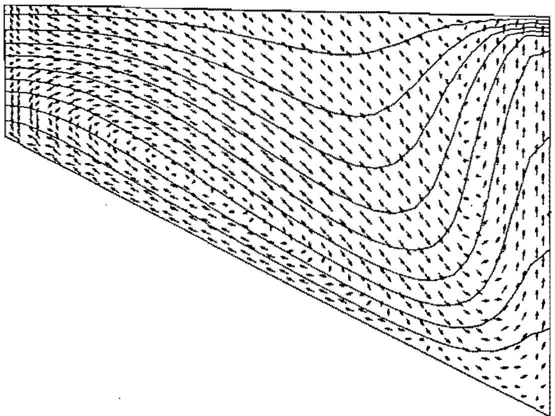

Fig.5.3 Computed flow pattern and temperature at 560,000 years for the same conditions as figure.5.1.

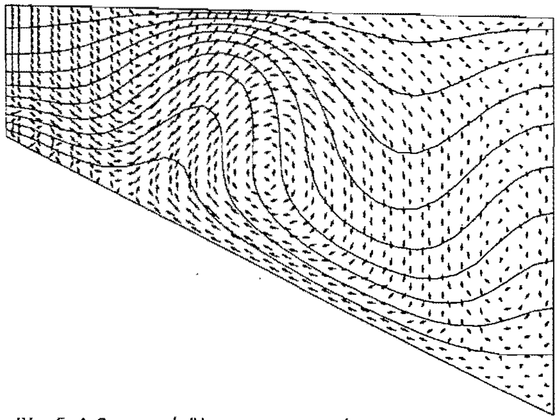

Fig.5.4 Computed flow pattern and temperature at 660,000 years for the same conditions as figure.5.1.

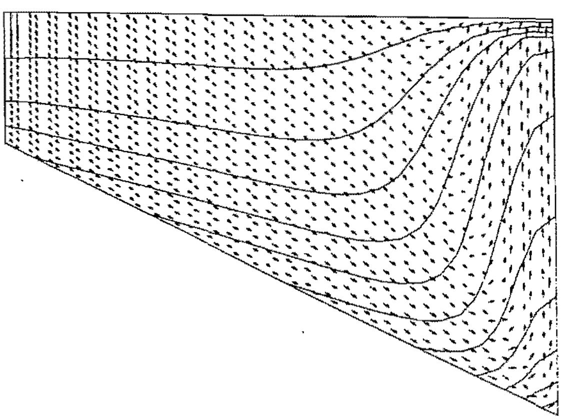

Fig.6.1 Computed flow pattern and temperature at 500,000 years with topographic effect added to the conditions of figure 2(nearly steady state).

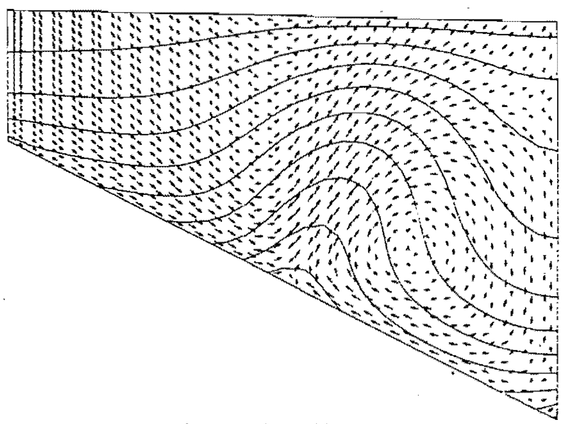

Fig.6.2 Computed transient flow pattern and temperature at 200,000 years during development of the steady state in figure 6.1.

mal systems, long period oscillatory behavior of this sort cannot be detected in practice. Not all such solutions are oscillatory ; variations of the input parameters can produce steady solutions resembling Figure 5.1, with a dominant upflow zone located midway above the sloping bottom. This type of flow pattern appears to characterize some practical field situations(Yano et.al.,1987). If heat is instead provided by a fixed heat boundary condition, the steady solution depicted in Figure 6.1 results; during the development of the steady flow, however, the flow passes through an intermediate stage shown in figure 6.2(note the resemblance to Figure 5.1).

Among all of the rock properties, the distribution of permeability is the most important and is the hardest to categorize, owing to its extreme variability in nature. Preliminary convective flow models(such as those discussed here) necessarily assume that the permeability is homogeneous, but subsequent calculations should examine the influence of permeability heterogeneities. The presence of an overlying caprock is a case of obvious interest; Yano et al,(1987b) have shown that the character of the influence of a caprock on the flow depends qualitatively upon the location of the heat flux boundary.

Three-dimensional effects are clearly important for real reservoirs. As Yano(1987) noted, rotating the model of Figure 5.1 about its right-hand edge produces a representation of a circular caldera system; in such a case, the influence of topographic drive becomes more important and forces the upflow zone down slope, closer to the caldera center.

The deep heat sources considered so far are broadly distributed in a regional fashion. If a discrete fault or fracture zone penetrates the otherwise impermeable basement, mass and heat will flow into the aquifer at a point along the bottom. Calculations for such a case were performed(involving (1)topographic influence at the surface, (2) a uniform basal heat flux, and (3) a point source of hot fluid located midway along the sloping basement). At an early stage of the transient convection, the flow is mainly controlled by the point source even if the input thermal power from the point source is less than that for the extended heat source distributed along the boundary, forming a rising hot plume above the point source. The influences of the topographic gradient become more predominant afterward, and the net flow sweeps the heat from the point source to the right boundary, resulting in a strong upflow along the boundary.

4. IMPLICATIONS

Even if attention is restricted to elementary geometrical slopes and simple prescriptions for boundary conditions, a wide variety of hydrothermal convection patterns are possible, as has been shown. The effects of combining various driving mechanisms are difficult to predict in advance. Consequently, even if a particular geothermal field has such a simple structure, it may be difficult to interpret the entire conditions given from a simple data set of the field. If a catalogue of known solution is available in advance, however(similar to the catalogue of MT solutions assembled by Ogawa et al,(1985), for example), then more informed judgments may be made. The models presented here are offered as a modest contribution to such a catalogue.

Acknowledgments.
The author would like to thank helpful review by J.W. Pritchett.

5. REFERENCES

Hanaoka, N., 1986, Structural control of hydrothermal system by gravity basement, J. Geothermal Res. Soc. Japan, vol.8, no.4, pp.379-412.

Ogawa, Y., Sato, I., and Kikuchi, T., 1985, Magnetotelluric method two dimensional calculation catalogue. Geological Survey of Japan, 448p.

Yano, Y., 1987, Parameter sensitivity of convection in a caldera. Proceedings, 77th SEGJ Conference, pp.255-259.

Yano, Y., Kamata, H., and Ogawa, K., 1987a, A model of hydrothermal convection in the Shishimuta caldera, Central Kyushu. Proceedings, 76th SEGJ Conference, pp.255-260.

Yano, Y., Kamata, H., and Ogawa, K., 1987b, On the conditions for the formation of a hot water convection system above the slope of a caldera basement: Modeling of Shishimuta caldera, Central Kyushu. J. Japan, Assoc. Petrol. Technol., vol.52, no.5, pp.399-412.

Yusa, Y., 1983, Numerical experiment of groundwater motion under geothermal condition - vying between potential flow and thermal convective flow. J. Geothermal Res. Soc. Japan, vol.5 no.1, pp.23-38.