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NUMERICAL MODELING OF THE EVOLUTION OF TWO-PHASE ZONE UNDER FISSURED CAPROCK

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ABSTRACT

A vapor-dominated two-phase zone would be formed in a geothermal reservoir under fissured caprock, if the permeability of the fissure is much smaller than a critical permeability which is estimated by an energy balance. If the permeability of the fissure is large, then the rule of minimum mass input would be applied.

INTRODUCTION

Yano and Ishido(1989) discussed about the conditions for the development of two-phase zones under fissured caprock. Situations are found in many geothermal reservoirs in Japan where two-phase zones in the natural state and surface manifestations such as fumaroles may be related with permeable flow path through caprocks.

The Ginyu reservoir in the Kirishima geothermal field is characterized by surface manifestations along a fault and vapor-static pressure profile in the upper part of the reservoir under the fault. A simple two-dimensional model was created after the Ginyu reservoir, and it was used for the discussion of the conditions for development of two-phase zones under fissured caprock. Ideas of the model settings in Ingebritsen and Sorey(1988) were taken into consideration.

Simulation results showed several things. (1) A two-phase zone may form so long as sufficient deep fluid mass recharge is present. (2) Or, so long as deep input energy is great enough. (3) The final steady states do not depend on initial conditions. For the simulations above in Yano and Ishido(1989), the permeability of the fissure was the same as that of the reservoir, and was pretty high. Pressure in the two-phase zones formed with large mass input were much greater than vapor-static. In order to create a two-phase zone with small mass input, extreme energy input was required. Both didn't match the actual situation.

After that, we made further elaborations on model parameters such as temperature of the deep input fluid and permeability of the fissure. In this paper, the results of the recent simulations are shown with brief review of the previous work. A part of the previous work was also shown in Yano et al.(1988), and a part of the recent simulations was shown in Yano and Ishido(1990).

THE GINYU RESERVOIR

The Ginyu reservoir is located in the Kirishima geothermal field which is one of the promising fields under exploitation for geothermal power plants in southern Kyushu in Japan(Figure 1). The Kirishima field is situated near the Kirishima volcanos which are located about five kilometers to the northeast. Several faults and lineaments trending ENE-WSW are related to hot springs, fumaroles and alteration zones. The most prominent geothermal anomalies are seen near the Ginyu fault and the Shiramizugoe fault. Geophysical surveys including gravity survey, electrical survey and surface heat flow measurements confirmed the configuration of the major faults and heat anomalies. Many wells were drilled in the Kirishima field, especially near the major faults for over ten years until now. Depth of these wells ranges from several hundred meters to over two thousand meters. Temperature and pressure measurements were performed in these wells.

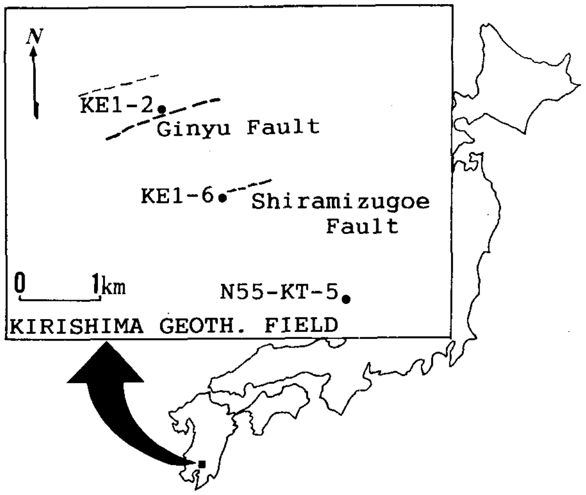

Fig 1. Location of the Ginyu reservoir, modified from Kitamura et al.(1988).

Figure 2 shows the relation between elevation and pressure(Kodama and Nakajima, 1988) in the Kirishima geothermal field. It is shown in this figure that there are two separate hydrostatic pressure-elevation relations. One of these is of the Ginyu reservoir. The slope of the fitted line corresponds to the hydrostatic pressure of hot water at 225 ℃. Measurements in the Ginyu reservoir shows uniform temperature at 232 ℃. The uniformity of temperature in the reservoir implies high permeability within it. In the upper part of the reservoir, pressure-elevation relations are clearly different from hydrostatic. They show vapor-static relations. Two phase zones are assumed by this data. Also, production tests in wells KE1-2 and KE1-6 showed very high steam content in the produced fluid(Kodama and Nakajima, 1988). Thus, a two phase zone with vapor-static pressure is supposed to exist over hydrostatic hot water zones in the Ginyu reservoir.

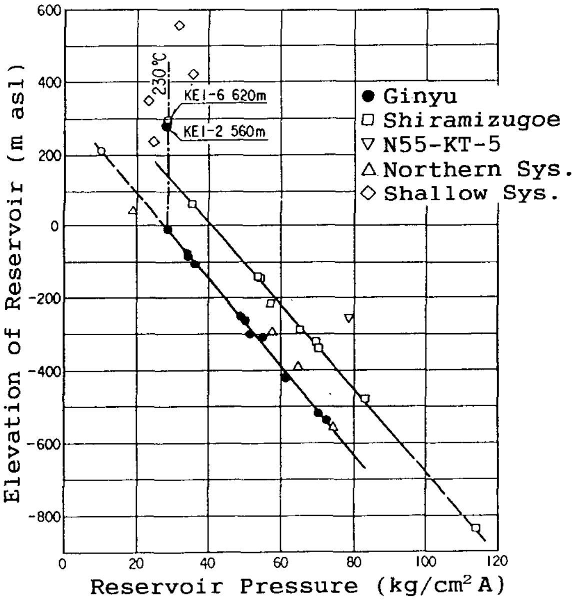

Fig 2. Pressure-elevation relationship in the Ginyu reservoir (Kodama and Nakajima,1988).

The Ginyu fault is featured by a 200m wide subsided zone, active fumaroles, hot springs, an alteration zone, an ENE-WSW lineament, a low resistivity zone, and an anomaly of mercury(ditto). A low permeable layer of 200m to 400m thickness at the depth of several hundred meters is supposed to exist over the geothermal area. The low permeable layer is a lava layer, in which fractures are filled with alteration minerals. Highly permeable reservoirs are developed under the low permeable layer in the Kirishima area.

Figure 3 is a schematic model of the Ginyu reservoir based on above considerations. The deep hot water supply is essentially meteoric water which is heated up by the heat source of the Kirishima volcanos. It is fed into the high permeable Quaternary volcanic layer under the low permeable alteration layer through the deep part of the Ginyu fault. At the top of the hot water reservoir, a two phase zone is formed under the low permeable caprock. Some of the steam is running out of the reservoir through the Ginyu fault to the surface, and forms fumaroles and hot springs.

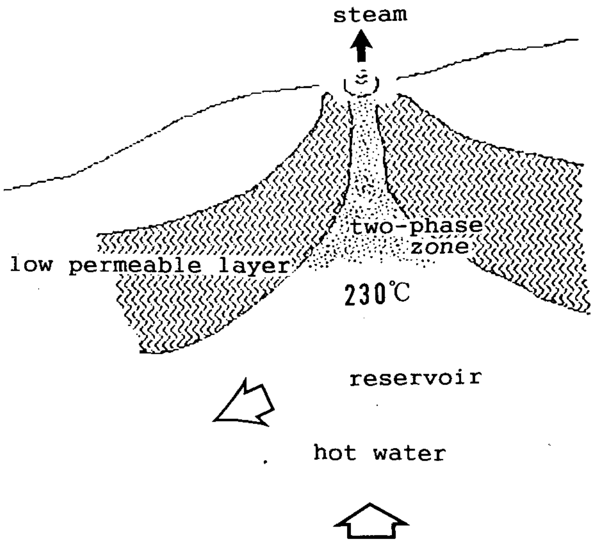

Fig 3. Schematic model of the Ginyu reservoir.

NUMERICAL RESERVOIR MODEL

In order to study the Ginyu type reservoir, we set up a numerical model with geometric components shown in Figure 4. This rather simplified two-dimensional vertical section model incorporates many of the major structural features of the Ginyu reservoir. Quantitative details concerning the representation are summarized in Yano and Ishido(1989).

The size of the highly permeable reservoir, designated as A in Figure 4, is about one square kilometer in vertical section, which is inferred from exploration data. The reservoir is covered by a low permeable altered caprock(D). There is a permeable conduit(F) between the reservoir and the land surface through the caprock. Here we call it a fissure. In the Ginyu area, the fissure corresponds to the Ginyu fault. It is a fractured zone which has some width. Below the reservoir, a permeable conduit(E) also related to the Ginyu fault is supposed to exist for hot water(Mo) to flow into the reservoir. The reservoir is located at a high elevated place related to the volcanic activity. We assume a steady state for the natural state of the system, so the mass inflow rate into the reservoir and the outflow rate must be balanced. A horizontal permeable conduit(B) is assumed for this mass balance. Country rocks(C) around the reservoir have some permeability compared to the caprock, but it is very small, so heat conduction is dominant in them.

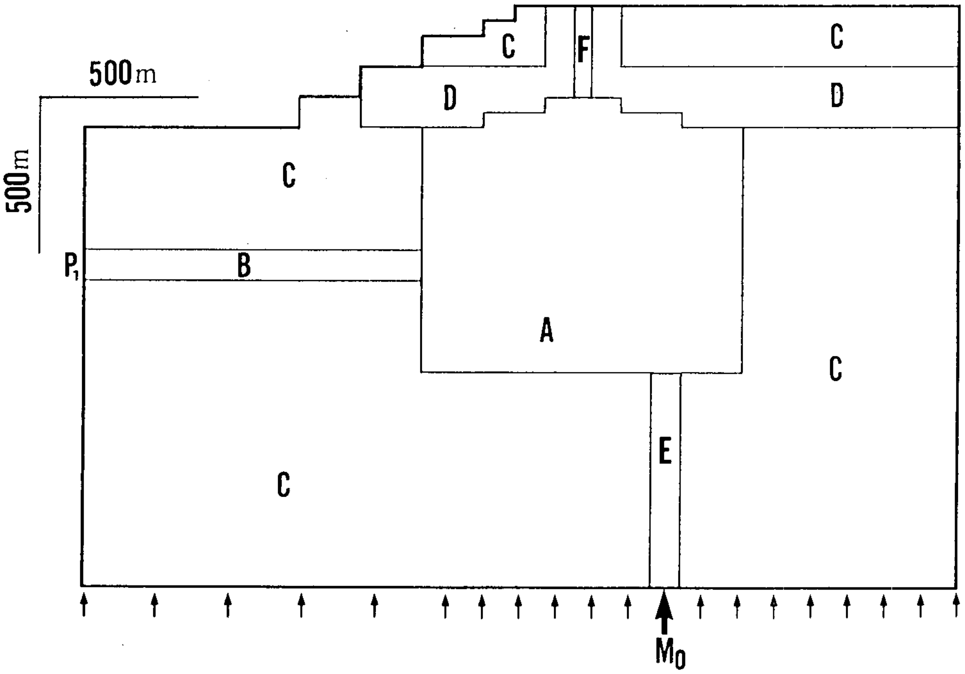

Fig 4. Geometry of the numerical model.

Both side boundaries are insulated except for the outlet of the horizontal conduit. The pressure there(P_1) is hydrostatic pressure which corresponds to initial temperature gradient. The initial pressure of the system is hydrostatic pressure, and the initial temperature gradient is conductive profile according to heat flux from bottom. The heat flux from bottom(intensity designated by arrows) is high on the right part of the system where land surface is elevated. As the heat flow boundary condition of the upper surface of the system, we used "convective-radiative" boundary condition (J.W.Pritchett, personal communication). Details are also shown in Yano and Ishido(1989).

Numerical calculations were all performed using the THOR reservoir simulator (Pritchett,1988), which is designed to solve multidimensional unsteady multi-phase problems in geothermal reservoir flow.

PREVIOUS RESULTS

Using the numerical model in Figure 4, we performed simulations of the evolution of two phase zone in the natural state. We started with conditions that temperature of the deep input fluid is about 260 °C, and the permeability of the fissure is 100 md, which is as same as the permeability of the reservoir. We expected that, if the deep inflow rate exceeds the flow rate through the horizontal conduit, then fluid would flow upwards into the fissure and form a two-phase zone; otherwise, downflow in the fissure would occur.

The amount of mass flowing out of the reservoir through the horizontal conduit(Mesc) can be roughly estimated by the following equation:

$$Mesc = k A (Pa - P_1) / (\nu L) \quad (1)$$

where k, A and L are the permeability, cross-section area and length of the horizontal conduit. The kinematic viscosity of water is represented by ν. P_1 is the boundary pressure applied at the conduit outlet(see Figure 4), and Pa is the initial hydrostatic pressure below the fissure at the elevation of the conduit (8.5 MPa). Assuming appropriate viscosity for the fluid, we calculated the value of Mesc by equation (1) as 47 kg/s.

Actually, simulations showed that a two-phase zone is formed with Mo greater than 47kg/s, and that it is collapsed by the downward flow of cold water with Mo less than 47kg/s.

We tried Mo = 100 kg/s at the beginning and reduced it gradually until it becomes less than the critical rate. For each set of conditions, calculations were continued until nearly steady states were reached. One to five thousands simulated years were needed for these calculations. Figure 5 is a steam saturation distribution for Mo = 60 kg/s. The highly saturated steam is restricted in the uppermost grid block in the fissure. But this two-phase zone is larger than those formed with larger mass input. Temperature in the reservoir becomes nearly uniform at the inflow temperature, though pressure at the fissure is much higher than vapor-static pressure, even higher than the hydrostatic pressure if Mo is as large as 100 kg/s. We cannot expect a vapor-dominated two phase zone in this case of very high fissure permeability. Even a two-phase zone is formed by

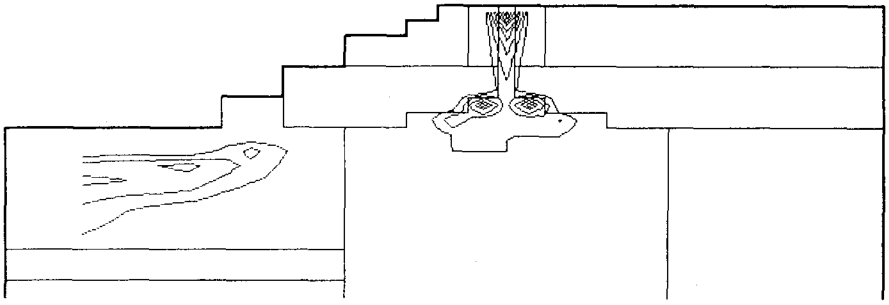

Fig 5. Computed steam saturation with highly permeable fissure, large mass source from below at temperature 260 °C(Yano and Ishido,1989). Contour interval is 0.05.

mass input larger than the critical rate, it is collapsed by downflow of cold water when the input mass becomes a bit smaller than the critical. If Mo is less than 47 kg/s, we cannot sustain the two-phase zone unless we assume extremely large energy input accompanying the mass input.

In the whole simulation work for this paper, we tried various conditions and their change at certain time stages. But we couldn't find different final steady states for the same final conditions, even if the histories of them are different.

EFFECT OF TEMPERATURE OF DEEP INFLOW

The internal energy of deep inflowing fluid we used in the above simulation corresponds to hot water at temperature about 260 °C. Because the permeability of the reservoir is pretty high, the hot water spreads within it at a considerable speed. As a result, temperature within the reservoir becomes almost uniform at 260 °C. In the Ginyu reservoir, uniform temperature at 232 °C was observed (Kodama and Nakajima,1988), which indicates high permeability of the reservoir. As long as the permeability through the entire system including the deep conduit, the reservoir and the outlet conduit is so high, the reservoir temperature is controlled by the deep inflowing fluid. If it is the case with the Ginyu reservoir, the deep inflow temperature should be 230-240 °C.

We tried to see how the state would be changed by the change of temperature of deep inflow. We made calculation with Mo = 48 kg/s. As was described above, a significant two-phase zone was formed as long as the temperature of the deep inflow is about 260 °C. Instead, we tried simulation with temperature at about 240°C. As a result, we could not form two-phase zones in the reservoir by this temperature, except for the uppermost grid block in the fissure.

Then we made calculation with temperature at about 280 °C. Figure 6 shows the computed two-phase zone under this condition. Compared to the result with deep input temperature at 260 °C, steam saturation in the two-phase zone becomes higher and the size of the zone also becomes larger. However, steam saturation in the fissure itself is still small, and the pressure gradient is still far larger than a vapor-static pressure. Furthermore, though this is a large and substantial two-phase zone, we found this two-phase zone was also collapsed when we reduced the deep inflow mass rate Mo to 42 kg/s, which is less than the critical rate 47 kg/s.

As we see in the above simulations, the size and saturation of the two-phase zone are sensitive to the temperature of deep inflowing fluid. However, a vapor-static pressure is not attained, and the criteria of minimum mass input is applicable to these high-permeable fissure cases.

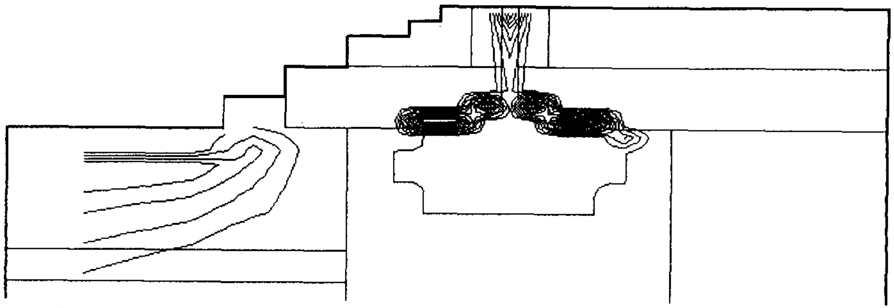

Fig 6. Computed steam saturation with highly permeable fissure and source fluid at temperature 280 °C.

EFFECT OF PERMEABILITY OF FISSURE

In case of the Ginyu, permeability of the reservoir is estimated to be uniformly high, based upon well data. However, permeability of the fissure which connects the reservoir and land surface is unknown. In the simulations above, we have supposed it to be 100 md which is as same as the reservoir. The very high permeability enables a large amount of steam to flow up to the surface forming active fumaroles, when the pressure in the reservoir is maintained by a large deep mass input. But if the deep mass input is small, the high permeability of the fissure allows cold surface water flow down into the reservoir.

For a large vapor dominated two-phase zone to be sustained, high permeability through the caprock is unfavorable. If there is no permeable conduit in the caprock, an extensive vapor dominated two-phase zone would be formed. Actually, we got a highly vapor-saturated, large two-phase zone when we made the net vertical permeability of the fissure to be zero. But if we assume that the reservoir is completely sealed by impermeable caprock, the existence of active fumaroles or other surface manifestations are hard to be explained. The fissure must have permeability to some extent for steam to flow up.

However, if the permeability of the fissure is small, the minimum mass input criterion may become ineffective as we saw in the case of extreme energy input(Yano and Ishido,1989), where small mass recharge from the deep conduit makes a large, vapor dominated two-phase zone. The idea is that, if the cooling rate from above by the downflowing cold water in the fissure at a vapor-static pressure gradient is trivial compared to the cooling power needed for changing the total vapor-phase mass produced per unit time into liquid phase, the two-phase zone would not be collapsed.

The downward convective cooling flux from above for zero vertical pressure gradient is given by $Af \cdot kf \cdot Cvf \cdot \rho \cdot g \cdot \Delta T / \nu$, where Af is cross sectional area of the fissure, kf is the permeability of the fissure, Cvf is fluid heat capacity, ρ is fluid density, g is acceleration due to gravity, ΔT is temperature difference across the fissure zone, and ν is fluid kinematic viscosity. The cooling power needed is given by $Mo \cdot X \cdot Hsw$, where X is the mass fraction of vapor-phase produced from the upward hot water flow, and Hsw is the latent heat at the two-phase zone temperature. X can be calculated by a simple energy conservation equation of the source hot water and fluids in the two-phase zone. If we assume that the downward cooling flux is much smaller than the needed cooling power, then the following inequality is derived.

$$kf \ll Mo\ X\ Hsw\ \nu \ / \ (Af\ \rho\ g\ Cvf\ \Delta T) \qquad (2)$$

Assuming the two-phase zone temperature to be 230 °C, the source fluid temperature to be 280 °C,and Mo to be 36 kg/s, the right side of the inequality (2) is roughly estimated as 20 md.

Figure 7 is calculated steam saturation of a model in which permeability of the fissure is 5 md. Temperature of the deep inflow is at 280 °C, and mass input rate is 36 kg/s which is less than the critical mass rate. If permeability of the fissure is very high, cold water downflow will occur as we found it previously. But in this case, steam saturations at the top of the reservoir and the fissure are very high, forming a large vapor-dominated two-phase zone. As expected, we could make a substantial two-phase zone with small mass input and small permeability of the fissure. Mass of the rising steam and the liquid water in the uppermost grid block(depth of centroid is 25 m) of the fissure is 2.1 kg/s and 2.0 kg/s respectively. In the grid block whose depth of centroid is 125 m in the fissure, 3.9 kg/s of steam is rising and 0.007 kg/s of liquid water is flowing downward. That is, the fluid rising in the fissure is mostly steam in lower level, but a part of it becomes liquid water as it reaches to the shallow part.

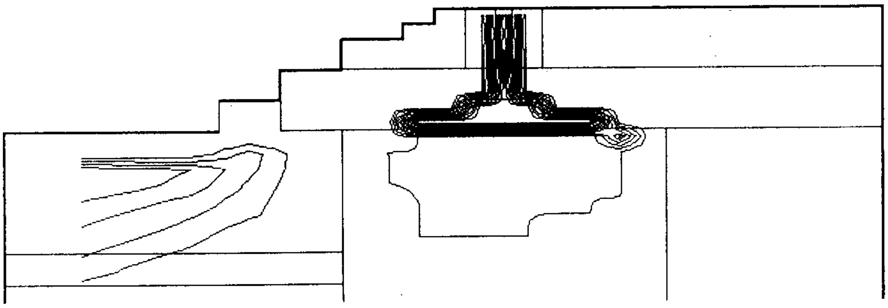

Fig 7. Computed steam saturation with low permeable fissure and small mass source at temperature 280 °C.

SUMMARY

Two-phase conditions in geothermal reservoirs with fissured caprocks in the natural states are greatly influenced by the permeability of the fissure, as we found it in the last calculation.

As far as the permeability of the fissure is very high, the rate of mass input from below determines whether there is a downflow of cold water in the fissure or not. A minimum mass input rate is required to sustain the two-phase zone. This critical mass rate is given by equation (1). Even though the temperature of the deep inflow has influence on size and steam saturation of the two-phase zone, the steam saturation in the fissure is small and the pressure gradient is much higher than the vapor-static profile in the case of this "mass-sustained two-phase zone".

On the other hand, if the permeability of the fissure is so small that the amount of downflowing cold water in the fissure is negligible compared to the produced steam in the two-phase zone, a vapor-dominated two-phase zone can be sustained by a small mass input from below. The permeability of the fissure must be small enough as given by inequality (2) for this "heat-sustained two-phase zone".

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