MODELLING STUDIES OF THE EVOLUTION OF VAPOUR-DOMINATED GEOTHERMAL SYSTEMS

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SUMMARY – Numerical experiments, based on linear stability results, are invoked to model the evolution of two-phase vapour-dominated zones within geothermal systems. A reservoir model with all boundaries impermeable to fluid flow and a uniform heat flux at the bottom boundary is used. The results obtained show that different steady-states are accessible along different quasi-static paths from the same initial vapour-dominated steady-state. Thus, the realization of a steady-state with a two-phase vapour-dominated zone overlying a single-phase hot water region can indicate that the geothermal system undergoes a process of slow cooling. A steady-state with a two-phase vapour-dominated zone overlying a single-phase vapour region can be formed either as a result of slow heating or as a result of a reduction in permeability. A steady-state with an upper vapour-dominated part and a lower liquid-dominated part can occur if permeability of the system has been gradually increased.

1 INTRODUCTION

Field measurements taken from the geothermal systems at Wairakei in New Zealand, The Geysers in California and Larderello in Italy demonstrate the presence of a two-layer structure. The upper layer is characterized by almost constant temperature and pressure, which are close to corresponding saturation values. Immediately at the top of the lower layer, temperature gradients change to values much higher than those of the upper layer. To summarize, the following three conceptual models (steady-states) based on these observations have been proposed in geothermal literature. In the model of White *et al.* (1971) a two-phase vapour-dominated zone occupies a region over a single-phase water zone *(steady-state A)*. This model is in good agreement with the Wairakei observations, as given in the work of Allis and Hunt (1986). Truesdell (1991) suggests that a two-phase vapour-dominated zone overlies a single-phase vapour region *(steady-state B)*. This is consistent with recent deep drilling results from The Geysers (Walters *et al.*, 1988). In the model of Pruess *et al.* (1987), proposed for Larderello, a two-phase region has two parts: an upper vapour-dominated part and a lower liquid-dominated part *(steady-state C)*.

This paper suggests that steady-states *A*, *B* and *C* are accessible from the same initial steady-state, but along different quasi-static paths. To validate this hypothesis, four series of numerical experiments representing four different quasi-static processes were run from the same initial vapour-dominated state:

Process 1 – slow cooling of the reservoir by decreasing the amount of heat transported to its base.
Process 2 – slow heating of the reservoir by increasing the amount of heat transported to its base.
Process 3 – gradual decrease in permeability of the reservoir.
Process 4 – gradual increase in permeability of the reservoir.

A quasi-static process is an idealization that can be applicable to geothermal systems. A natural geothermal process can be approximated by a quasi-static process with almost any degree of accuracy. Processes 1 and 2, for example, may approximate changes in conductive heating at the base of a geothermal system as a result of changes in igneous activity. Processes 3 and 4 may reflect permeability decrease or increase in response to deposition or dissolution of chemicals respectively.

2 NUMERICAL RESULTS

2.1 Numerical model

The model used here is a geothermal reservoir with all boundaries impermeable to fluid flow, so that the amount of water trapped in the pore space is constant at all times. A uniform heat flux is imposed at the bottom boundary. Heat loss is allowed through the upper boundary (a cap-rock) via conduction. For relative permeabilities Grant's curves (Grant, 1977) are chosen. Capillary pressure is neglected in the present analysis. The following parameters were held constant in all simulations performed: rock density = $2650\ kg/m^3$; rock matrix heat capacity = $1000\ J/kg\ deg\ C$; rock thermal conductivity = $3.2\ w/m\ deg\ C$; porosity = 0.03; residual liquid saturation = 0.25; residual vapour saturation = 0.05; reservoir depth = $1000\ m$.

As the initial state, a balanced vapour-dominated counterflow was chosen. The initial reservoir permeability k was $10^{-14}\ m^2$. A constant heat flux of $0.5\ w/m^2$ was imposed at the base of the reservoir. A very large heat capacity was prescribed at the top of the reservoir to keep its temperature around $240°C$. The numerical simulator *TOUGH2* (Pruess, 1986) was used. A one-dimensional numerical grid was selected. The simulations were run from the initial state to the neighbouring steady-state and so on.

2.2 Process 1 – cooling

In this series of numerical experiments we perturb the reservoir slightly by decreasing heat flux at the bottom boundary. A smaller heat flux at the bottom boundary produces a drier vapour-dominated zone with smaller liquid phase saturation. The excess of water gathers at the bottom of the reservoir. The reason for this favorable location is the direction of the propagation of small disturbances of the saturation field. Linear stability results show that small disturbances of the saturation field, produced by the new boundary condition, travel from the top to the base of the reservoir and cause the formation of steady-state A with a single-phase liquid zone below a vapour-dominated region. Fig. 1 shows liquid saturation distributions inside the reservoir for different values of heat flux Q.

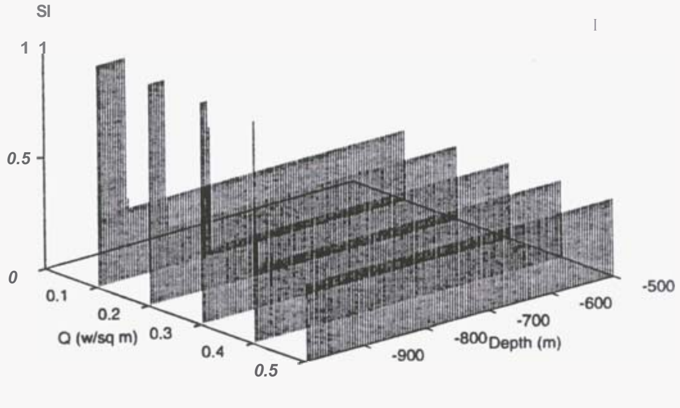

Figure 1. ***Process*** 1 – liquid saturation distributions calculated for intermediate steady-states.

Calculated temperature and pressure distributions for different values of heat flux Q are shown in Fig. 2 and Fig. 3 respectively. The location of the interface between two-phase and single-phase regions is indicated by a discontinuity in temperature and pressure gradients. In the counterflowing zone the heat-pipe mechanism of heat transfer prevails. Heat transfer in the liquid zone occurs by conduction only. In all simulations performed the Rayleigh number calculated for the liquid zone is well below the critical values for the onset of free convection and boiling, as given by Ribando and Torrance (1976) and Bau and Torrance (1981). Thus, the state of the liquid zone remains purely conductive and stable.

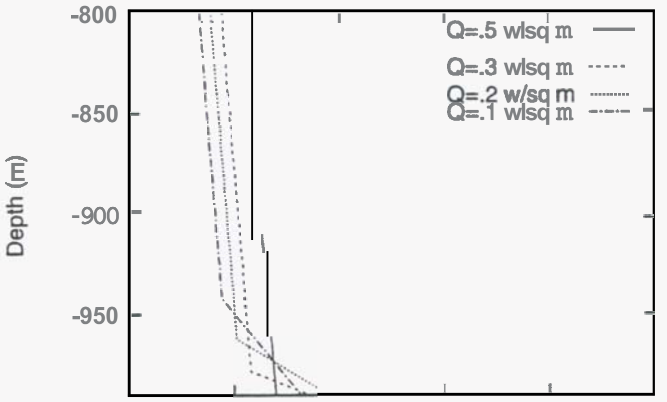

Figure 2. ***Process*** 1 – steady-state temperature distributions for different values of heat flux Q.

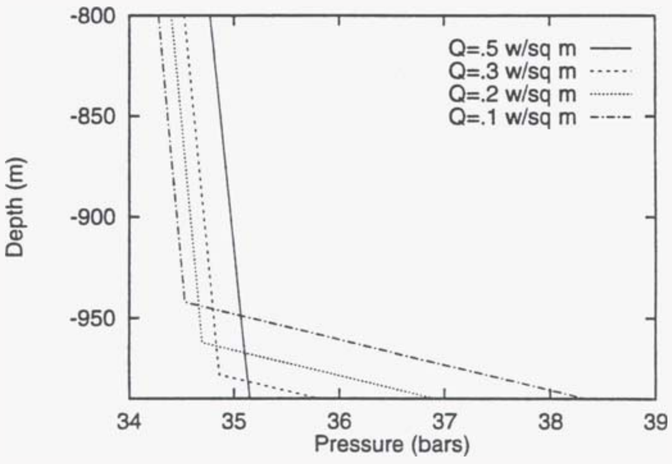

Figure 3. ***Process*** 1 – steady-state pressure distributions for different values of heat flux Q.

2.3 Process 2 – heating

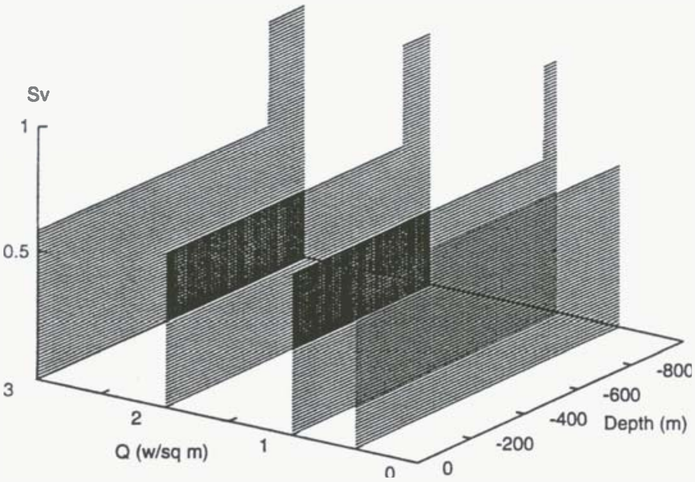

Figure **4**. ***Process 2*** – vapour saturation distributions calculated for intermediate steady-states.

In every step of this series of numerical simulations we increase the heat flux Q at the bottom boundary by a small amount. The perturbed system undergoes a quasi-static process, which results in the formation of steady-state B with a single-phase vapour zone below a two-phase region. Higher heat fluxes at the bottom boundary produce higher liquid phase saturations in the two-phase region of the reservoir. Balanced vapour-liquid counterflow cannot exist everywhere in the system, simply because there is not enough mobile water in it. Therefore, a single-phase vapour zone develops near the bottom of the reservoir as shown in Fig. 4. This is an exceptional configuration of a heavier fluid (a water-steam mixture) overlying a lighter fluid (pure vapour). Such configurations, however, are likely to exist, as shown in theoretical investigations by McGuinness and Young (1994).

Fig. 5 and Fig. 6 show temperature and pressure distributions calculated for intermediate steady-states corresponding to different values of heat flux Q. Numerical calculations indicate the presence of a two-layer structure with nearly constant temperature in the upper part and an abrupt temperature increase in the lower part. Pressure gradient in the lower part remains small. This is characteristic for pure vapour zones, where heat is transported mainly by conduction.

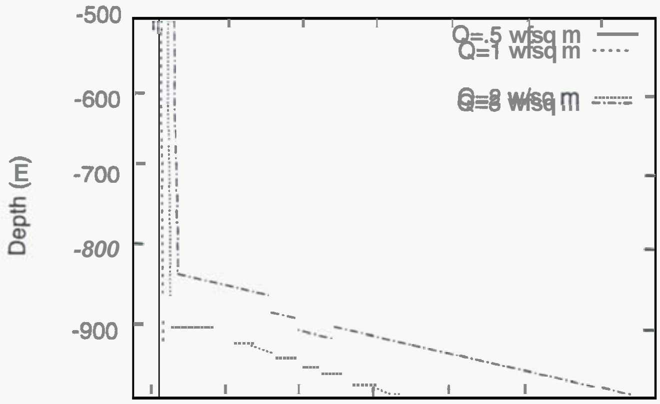

Figure *5*. ***Process 2*** – steady-state temperature distributions for different values of heat flux Q.

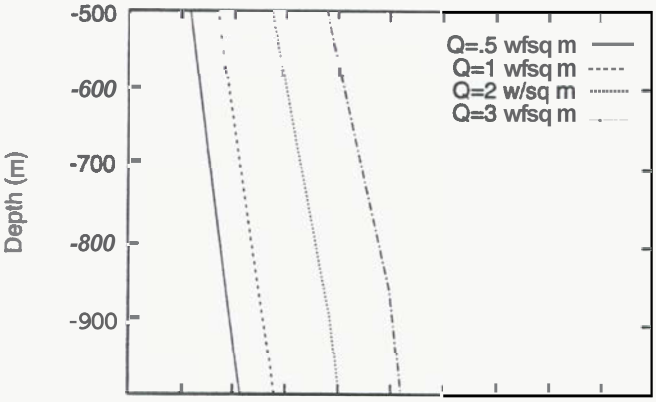

Figure 6. ***Process 2*** – steady-state pressure distributions for different values of heat flux Q.

2.4 Process 3 – permeability decrease

Process 3 is an alternative process leading to steady-state B. In every step of this process we decrease the permeability of the reservoir by a small amount and wait until a new steady-state develops. For a permeability range of 10 to 0.5 md the flow patterns are similar to those of process **2.** Further decreases in permeability to k as low as 0.04 *md* lead to somewhat controversial steady-states. The controversy of these steady-states is contained in relatively high liquid saturations of two-phase regions. For example, when k is equal to 0.04 *md,* calculated liquid saturation S_l exceeds **70%.**

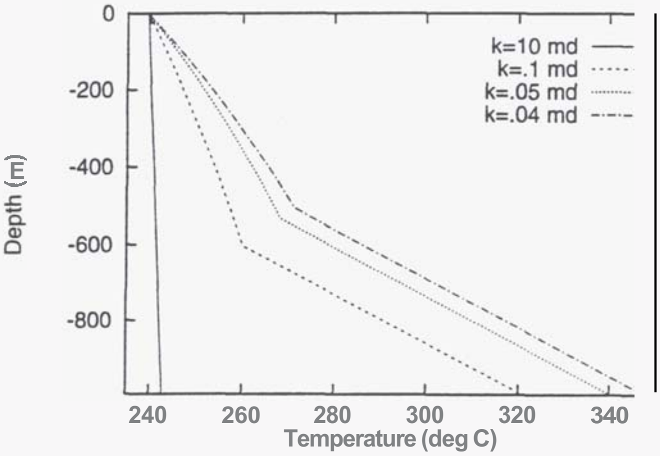

Figure 7. *Process 3* – steady-state temperature distributions for small k.

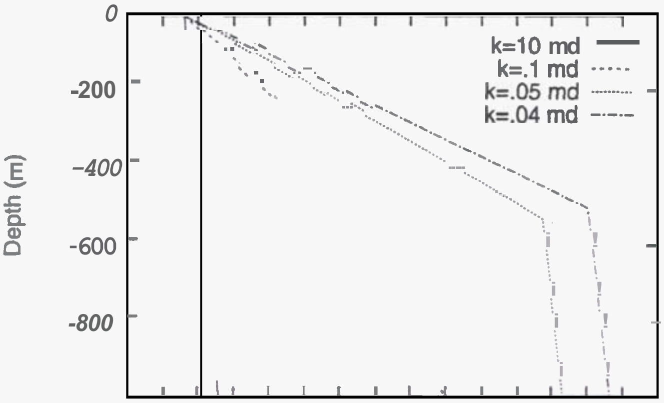

Figure 8. *Process 3* – steady-state pressure distributions for small k.

Temperature and pressure distributions calculated for these steady-states are shown in Fig. 7 and Fig. 8 respectively. The initial vapour-dominated state, corresponding to $k = 10$ *md,* is shown by a solid line. Again the formation of a two-layer structure with an abrupt interface is observed. The lower regions with vapour-static pressure gradients and sub-critical temperatures are obviously pure vapour non-flowing zones. The steady-state conditions of the upper regions are very interesting. Pressure and temperature gradients calculated for these regions could be interpreted as liquid-dominated, especially in conjunction with high liquid saturations obtained (Fig. 7 and Fig. 8). However the upper regions cannot be classified as liquid-dominated. Our results show that in every case considered relative permeability of vapour is still much larger than relative permeability of liquid. For example, when $k = 0.04$ *md,* numerical estimates give $S_l = 0.75$ and $k_{rl} = 0.26$, $k_{rv} = 0.74$. The latter indicates that vapour is the most mobile phase.

2.5 Process 4 – permeability increase

In every step of this series of numerical experiments we increase permeability k of the reservoir by small amount and wait until a new steady-state develops. An increase in permeability k (as well as a decrease in heat flux Q) leads to smaller liquid phase saturation in a vapour-dominated zone. Thus, there is an excess of water in the reservoir, which tends to gather near the bottom boundary in accordance with the direction of propagation of small disturbances. Since the scenario is similar to that of process 1, the formation of steady-state A could be expected. However it does not happen. Instead, steady-state C with an underlying liquid-dominated two-phase zone develops as can be seen in Fig. 9.

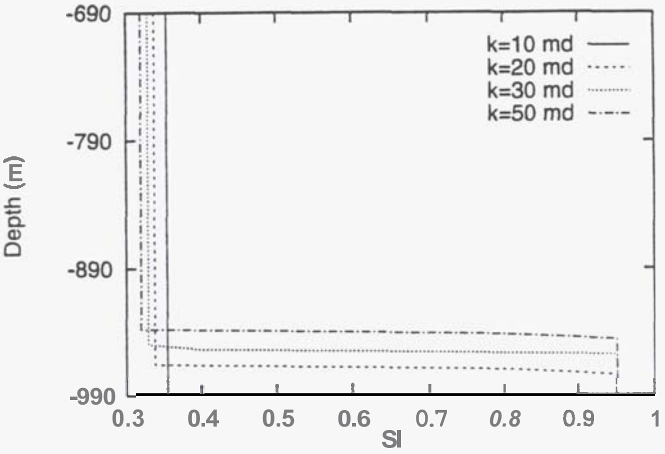

Figure 9. *Process 4* – liquid saturation distributions calculated for intermediate steady-states.

In Fig. 10 the temperature versus pressure plot, obtained from numerical simulations for $k = 50\ md$ (solid line), is compared with experimental saturation curve data (points). Experimental points falling exactly along the numerical curve indicate that the reservoir is fully two-phase.

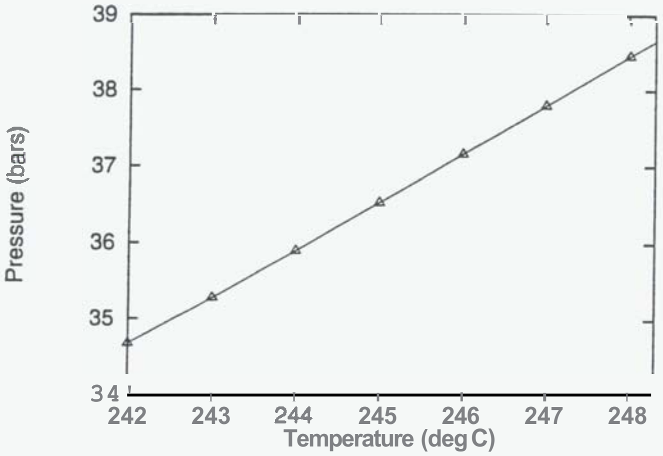

Figure 10. *Process* 4 – numerical pressure-temperature curve compared with experimental data.

The following explanation of the extension of two-phase conditions to the entire reservoir can be suggested. Firstly, conduction across a quiescent liquid layer is not sufficient for transporting the full amount of heat from the base of the reservoir. Secondly, according to experimental results of Bau and Torrance (1981), convection is not expected prior to the onset of boiling. Thus, liquid-dominated counterflow is the only possibility for the given set of parameters.

3 CONCLUSIONS

A numerical study of the evolution of two-phase geothermal systems has been performed. A reservoir with all boundaries impermeable to fluid flow and a uniform heat flux at the bottom boundary has been considered. The numerical simulator TOUGH2 (Pruess, 1986) has been used to investigate the response of a geothermal system to quasi-static changes in heat flux Q and permeability k. The formation of the following steady-states has been observed:

Steady-state A – a two-phase vapour-dominated zone overlying a single-phase hot water region.
Steady-state B – a two-phase vapour-dominated zone overlying a single-phase vapour region.
Steady-state C – a two-phase region with an upper vapour-dominated part and a lower liquid-dominated part.

These results are consistent with field observations from Wairakei in New Zealand, The Geysers in California and Larderello in Italy, where the presence of structures similar to *A*, *B* and *C* respectively was recorded.

The numerical results presented here have shown that the steady-states *A*, *B* and *C* are accessible from the same initial vapour-dominated steady-state, but along different quasi-static paths. Thus, the realization of *A* can indicate that a geothermal system undergoes a process of slow cooling (Q is decreasing). The state *B* can be formed either as a result of slow heating (Q is increasing) or as a result of deposition processes (k is decreasing). The state *C* can occur if the permeability of the system k has been gradually increased.

4 ACKNOWLEDGMENTS

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