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A BASIC MODEL FOR VAPOUR-DOMINATED GEOTHERMAL RESERVOIRS

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SUMMARY - In this paper the basic features which a model of a bottom-heated vapour-dominated reservoir must possess are described. It turns out that the essential components of a viable 1D steady-state model which includes a vapour zone are: a caprock/aquifer interface, a non-zero net mass upflow (excludes the geothermal heatpipe), and significant conduction. It appears that the combined significance of these three physical mechanisms has not been generally appreciated. There are additional constraints on caprock permeability (small) and the depth of the interface (sufficient).

1 Introduction

Geothermal fields designated as ***vupour-dominated*** (eg The Geysers, **USA;** Kawah Kamojang, Indonesia; Larderello, Italy; Matsukawa, Japan) typically produce fluid with enthalpy close to that of wet steam. Reservoir pressure profiles usually contain near vertical segments indicating a pressure gradient close to vapour-static. These geothermal fields also have a groundwater zone overlying the VD (vapour-dominated) aquifer. One problem has been to explain the apparent stability of such a system (water over steam) (Schubert ***et al.***, 1980).

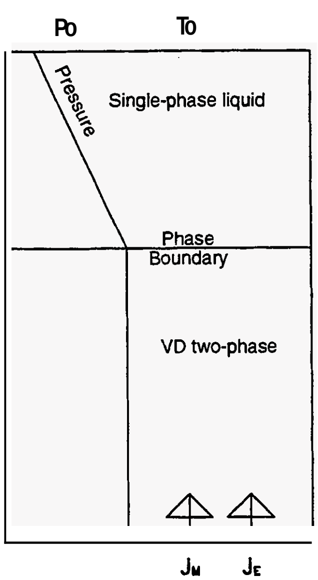

Figure 1: Schematic diagram of a VD reservoir

Straus and Schubert (1981) proposed a 1D model of a VD reservoir and applied the results to The Geysers and Kawah Kamojang. It is a homogeneous (constant permeability) **2** layer model, with liquid water lying over a VD 2-phase zone, Figure 1. The source at depth produces mass and energy at a fixed rate, and pressure and temperature are specified at ground surface. The derived pressure and temperature profiles fit the tabulated field data very well.

The Straus/Schubert model can be solved numerically, and the results used as initial data in a simulation experiment (Young, 1996). Figure 2 shows the initial VD steady-state (pressure P_v and temperature T_v profiles). In the 2-phase zone the pressure profile is close to steam-static, and fits the field data from Kawah Kamojang quite closely.

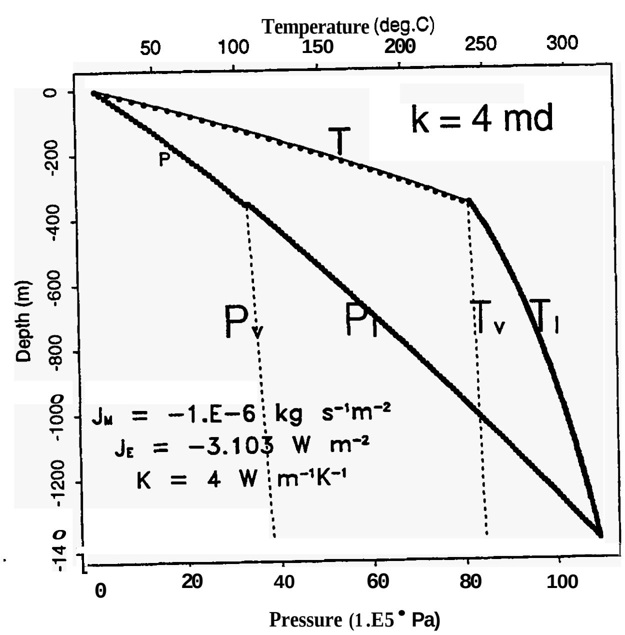

Figure 2: P and T profiles for the Straus/Schubert model

Beginning with this initial state the simulation soon reaches a final steady-state, but it is the ***liquid-dominated*** **(LD)** state (P_l, T_l), far from the **VD** initial state. Figure **3** shows the corresponding saturation profile (***NB*** the horizontal dotted lines in this and following figures indicate the assumed residual saturations). In fact the Straus/Schubert model is unstable to perturbations, and thus can not serve as a prototype for a **VD** reservoir (McGuinness and Young, **1994).**

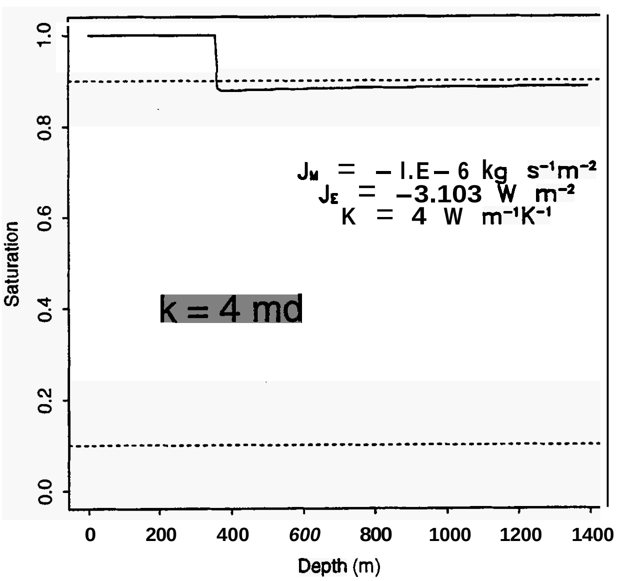

Figure **3:** Straus/Schubert model saturation profile

Straus and Schubert **(1981)** had some concerns about the stability of their model. Previous work by these authors (Schubert and Straus, **1980)** indicated that the configuration of liquid water over steam could be **gravitationally *unstable*** for large permeabilities. Their results suggested that a reservoir permeability of $k < .07$ md would be required for stability. Since this is too low for most **VD** geothermal fields, they proposed that such reservoirs must contain a **permeability contrast. VD** conditions could then develop in the low-permeability zone, and subsequently extend downwards into the geothermal aquifer. The obvious candidate for the permeability contrast is the caprock/aquifer boundary. Straus and Schubert did not actually construct their proposed model. In this paper I shall elaborate on their ideas and show which are the essential components of a **1D** steady-state model of a vapour-dominated reservoir.

2 Caprock Model Simulation

Figure **4** shows a computed saturation profile for a one-dimensional reservoir model which incorporates a low permeability layer (caprock), here chosen to lie between 300 and 500 m. The caprock permeability is **2** orders of magnitude lower than the aquifer permeability. **As** in the homogeneous case two-phase conditions develop at depth, but in contrast to Figure **3** a **VD** state is established within the caprock, associated with the low permeability of this structure. However, at the interface between the the caprock and the geothermal aquifer at 500 m $(P = 55$ bars) the positive permeability contrast (an increase downward) induces a liquid saturation increase to near fully-saturated conditions. Hence this extension of the Straus/Schubert model to include a caprock structure does not appear capable of representing a **VD** reservoir either.

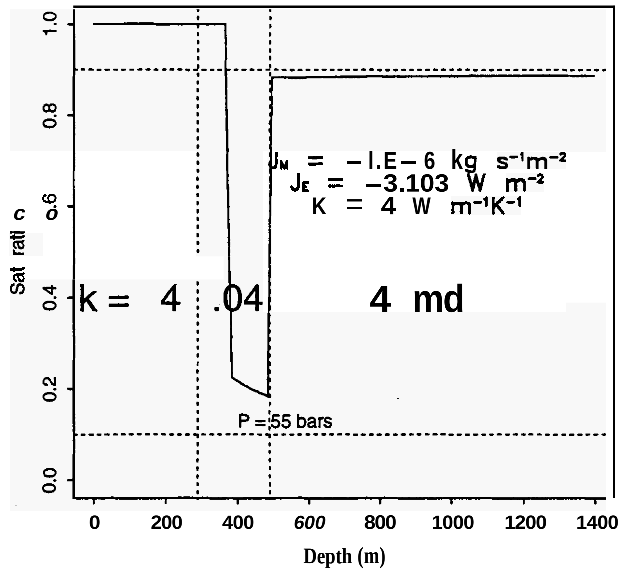

Figure **4:** Saturation profile for a caprock model

This could be taken to imply that the caprock mechanism does not provide an explanation for **VD** reservoirs. However Ingebritsen and Sorey **(1988)** have shown in a series of numerical experiments that a positive permeability contrast (increase downward) can be accompanied by a saturation decrease. Ingebritsen and Sorey's models were two-dimensional, and it might reasonably be concluded that vapour zone formation is therefore essentially a multi-dimensional phenomenon. However, we will show in this paper that a satisfactory **1D** model of a vapour-dominated reservoir can be constructed. This will also provide a physical explanation for the phenomena observed in Ingebritsen and Sorey's experiments.

3 A 1D Vapour-Dominated Reservoir

The essence of the caprock problem is seen to be the relationship between saturation and permeability gradient in a porous medium. In this section we shall give some general results and then apply them to the problem of natural state steam zone formation.

The relationship between mass flow J_M, energy flow J_E, conductivity K, permeability k, pressure P (or temperature T), and saturation S in the context of one-dimensional (vertical) steady-state two-phase geothermal flows has been recently examined in some detail (Young R.M., Classification of one-dimensional steady-state two-phase geothermal flows including permeability variations; Part **1,** theory and special cases; Part **2,** the general case, submitted to ***Int. J.*** **Heat** ***Mass Transf.***, **1996).** The first part of this study looked at the special cases of the geothermal heat-pipe, and high massflow situations when conduction could be ignored. In both these situations it was shown that a positive permeability contrast (eg at the caprock-aquifer boundary) always induces a saturation ***increase.*** This is a gravity-driven effect and is in the opposite direction to that controlled by capillarity (Stubos ***et al.***, **1993).** Conversely, a negative permeability contrast (eg at the aquifer-basement boundary) always induces a saturation ***decrease.***

These results show that the simulation experiment in Figure **4** is representative of a general pattern, and not just a freak occurence.

In the general case we need to consider the combined influence of non-zero net massflow and significant conduction in the presence of a permeability contrast. Figure 5 shows the relationship between saturation and permeability for the same reservoir parameters (J_M, J_E, K) used previously. Values similar to these were employed by Straus and Schubert **(1981)** in their model of the Kawah Kamojang geothermal reservoir.

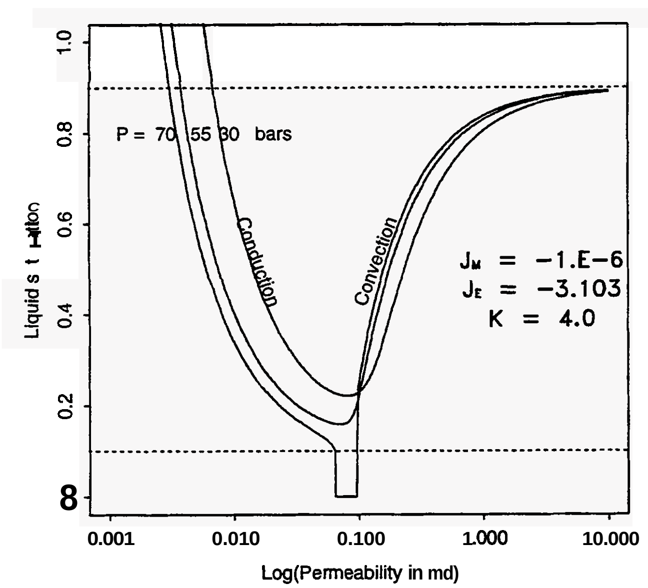

Figure 5: Saturation-permeability curves

Figure 5 shows the saturation-permeability relationship at a number of pressures. We shall approximate a permeability contrast **as** a discontinuity and assume that pressure is continuous across such a boundary. Then the saturation response to a permeability discontinuity (eg at the caprock-aquifer interface) can be determined by tracing along the appropriate curve in Figure 5.

First note that the right branch of all these curves has positive slope ($dS/dk > 0$). In this region a permeability ***increase*** will always be accompanied by a saturation ***increase.*** This is the situation already described, for convenience we refer to it as the convection-dominated regime.

Exactly the opposite happens on the left branch; here a permeability ***increase*** (downward) will induce a saturation ***decrease.*** We refer to this situation as conduction-dominated. Note that the left branch is entirely absent if either (a) net mass flow J_M is zero (a geothermal heat pipe); or (b) conduction K is negligible.

However, we must consider finite permeability jumps rather than the local gradients. In our application there is a jump from relatively low permeability within the caprock to high permeability within the aquifer. Let us suppose that this involves a jump from the left branch to the right branch of the permeability-saturation curve. Clearly this could involve a saturation increase ***or*** a saturation decrease, depending on the relative location of the initial and final flowpoints. However when the aquifer permeability is large (as in our case), the most likely response will be a saturation' increase, and this is precisely what is illustrated in Figure **4.**

Now for the dénouement: to gain an understanding **of** the physical mechanism behind natural state vapour zone formation we need to consider what happens to the S-k curve as pressure increases. We see from Figure 5 that it eventually intersects the vapour boundary $S = 0$ at a certain (drypoint) pressure value P_d (see Appendix). If there is a sudden permeability increase at a pressure $P > P_d$ then Figure **5** shows that a phase change can occur **as** a result, with a transition to single-phase vapour (actually the situation is more complicated than this but we must omit the details here). This is the basic mechanism behind natural state vapour zone formation.

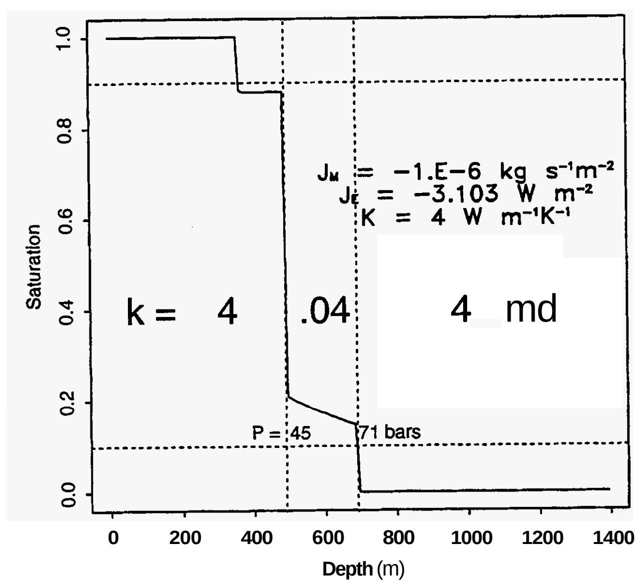

Figure 6: Saturation profile for a VD reservoir model

Figure 6 gives **an** simulation example. This is identical to Figure **4** except that the caprock layer has been translated downwards by 200m. As a result the pressure at the caprock-aquifer interface has increased to **71** bars. This is greater than the drypoint value, which for the current set of reservoir parameters is found to be $P_d = 62.8$ bars. Hence we expect a transition to single-phase vapour at the caprock boundary, and Figure 6 shows that this, in fact, occurs.

Comparing Figure 6 with Figure **4** we see that the caprock must be ***sufficiently deep*** for the vapour zone to form within the reservoir. It can also be shown that the caprock permeability must be ***sufficiently small*** $k < k_d$ for the mechanism to work. In the present case the drypoint permeability is computed to be $k_d = .079$ md so with $k = .04$ md the condition is satisfied.

In addition we should also mention that not all flows have high enough enthalpy to permit the intersection of the S-k curve with the vapour boundary, as shown in Figure 5. Such low enthalpy reservoirs will not develop a vapour zone at any depth. The relevant inequality is given in the Appendix.

Extension to two and three dimensions must be done numerically (Ingebritsen and Sorey, 1988). The vapour zone may then be vapour-dominated two-phase rather than single-phase because of the effect of the circulation. Nevertheless the same basic phenomena are observed.

4 Conclusions

Vapour zones may form in the natural state of geothermal reservoirs under special circumstances. A 1D formulation gives some insight into the physical constraints. For this case we can show that a vapour zone will develop in the geothermal aquifer provided it contains a caprock structure and:

- The upflow has sufficient enthalpy;
- The caprock is sufficiently tight;
- The caprock-aquifer interface is sufficiently deep.

All of these conditions have a precise quantitative expression. What is especially striking in our results is how a relatively small change in caprock permeability or caprock depth can induce a global net change in reservoir character, from liquid-dominated (Figure 4) to vapour-dominated (Figure 6), or vice-versa.

5 References

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6 Appendix

In the following note that the vertical coordinate is positive downwards. Hence the steady-state mass and energy upflows J_M, J_E are negative.

The drypoint pressure P_d referred to in the text is obtained by solving the following equation for pressure

$$-1 = \frac{\nu_s}{kg\Delta h\Delta\rho}[J_E - h_w J_M + \rho_w g\gamma] - \frac{\nu_w \nu_s J_M \gamma}{k^2 g\Delta h\Delta\rho} \quad (1)$$

where the function $k(P)$ (referred to as the drypoint permeability k_d in the text) is given by

$$k = \frac{J_M \nu_s \gamma}{J_E - h_s J_M + \rho_s g\gamma} \quad (2)$$

In these equations J_M, J_E are mass and energy flow, g is gravity and $\gamma = K(dT/dP)$ where K is conductivity and $T = T_{sat}(P)$ is the saturated temperature. The thermodynamical quantities are ρ density, ν kinematic viscosity and h enthalpy, indexed for vapour (s) or liquid (w). Then $\Delta h = h_s - h_w$ and $\Delta\rho = \rho_w - \rho_s$.

1D geothermal flows must have an enthalpy $h = J_E/J_M$ greater than a certain minimum value for vapour zones (as defined in this paper) to develop. The inequality that must be satisfied is

$$h > h_c - \gamma_c \rho_c g/(-J_M) \qquad \text{high enthalpy} \quad (3)$$

Here the subscript c denotes evaluation at the the critical point (P = **221.2** bars). In the present example the field enthalpy is 3.103 MJ/kg and the RHS of **(3)** evaluates to 1.6692 MJ/kg. Hence the inequality is satisfied.

The derivation of these formulae will be given in a forthcoming paper.