

THE FORMATION OF PERMEABILITY CONTRASTS IN GEOTHERMAL RESERVOIRS

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ABSTRACT

We present a model of a geothermal system supplied at depth by saturated steam. It is shown that as steam rises from depth to lower pressure regions, liquid forms for pressures greater than 3.1 MPa. Once the pressure reaches 3.1MPa and the steam continues to rise into even lower pressure regions, it becomes superheated. Condensate does not form in the zone where pressures are less than 3.1MPa.

The formation of condensate in regions where the pressure is in excess of 3.1MPa may lead to dissolution of the host rock. This in turn may lead to the formation of a higher permeability zone under a lower permeability 'cap rock'.

The depth of the transition point at which condensate no longer forms appears to be primarily controlled by the pressure at the base of the reservoir. The influence of the heat flux as an independent parameter is shown to be relatively small. The depth of the transition point appears to be constrained to ~350-400m.

This is an interesting result since the permeability in many vapour-dominated geothermal reservoirs is believed to increase significantly at around this depth.

INTRODUCTION

Many geothermal reservoirs are considered to have a low permeability cap rock overlying the bulk of the reservoir itself (White, Muffler & Truesdell, 1971; Ingebritsen & Sorey; 1988). In general terms, the cap rock is believed to be of sufficiently low permeability to prevent the reservoir from being flooded by cold groundwater aquifers, but sufficiently permeable so as to allow some fluid to enter and some fluid to exit in the form of hot springs, mud pots, geysers and fumaroles (Grant, Donaldson & Bixley; 1982). The permeability of the main reservoir rock however is deemed to be significantly greater than the overlying cap rock. Indeed, if this were not the case then it is difficult to envisage how fluid contained within the reservoir actually flows to wells. The notion of a low permeability cap rock overlying a higher permeability 'reservoir rock' is therefore a widely accepted concept.

Variations in vertical permeability are particularly important in the case of vapour-dominated reservoirs which are overlain with liquid-dominated regions. Ingebritsen & Sorey (1988) showed how the depth of the transition point between lower and higher permeability zones can effectively control the depth at which a reservoir can change from a liquid- to vapour-dominated state.

The concept of variations in vertical permeability raises an interesting question regarding how such a contrast can actually form. It is widely accepted that when geothermal reservoir liquids rise, cooling near the surface can lead to precipitation of minerals such as silica (Henley *et al.*, 1984); as the temperature of a liquid saturated in silica falls, silica will tend to precipitate out. Precipitation is therefore considered to be a significant factor leading to the formation of low permeability rocks over a geothermal reservoir.

In this paper we describe a further mechanism for the formation of low permeability rock overlying a higher permeability zone. We build on the work of Moore *et al.* (1998), who noted that mineral dissolution may arise due to the condensation of saturated steam at pressures greater than 3.1MPa, by developing a model of the system and determining the factors which determine the depth of the transition from a lower to a higher permeability rock.

ANALYSIS

Let us consider the steady state case in which the pressure P_1 and enthalpy h_1 are constant at some depth, and where (a) the pressure P_1 is greater than the pressure corresponding to the maximum enthalpy of saturated steam P^* , (b) the fluid is at saturation conditions and (c) the pressure gradient in the two-phase zone is less than hydro-(liquid) static but greater than vapour-static. We now develop a simplified steady state model in order to elucidate the processes involved in this system. For the purposes of our discussion we will consider a 1-D system such that there is no horizontal heat or mass transport and where vertical advection of heat is significantly greater than vertical conductive heat transfer.

As vapour rises from the base of the system and decompresses adiabatically ((i)-(ii), Fig. 1), the specific enthalpy of vapour increases. Consequently, a fraction of the vapour condenses and the liquid thus formed falls under gravity back to the source. This concept is in agreement with the notion that the pressure gradient is sub-hydrostatic. The process of partial condensation continues until the rising vapour reaches a pressure of 3.1MPa, the pressure P^* corresponding to the maximum enthalpy of steam h^* . As vapour continues to rise into lower pressure regions, it retains enthalpy h^* and becomes superheated, eventually venting from the surface as superheated vapour with pressure ~ 1 bar and enthalpy h^* .

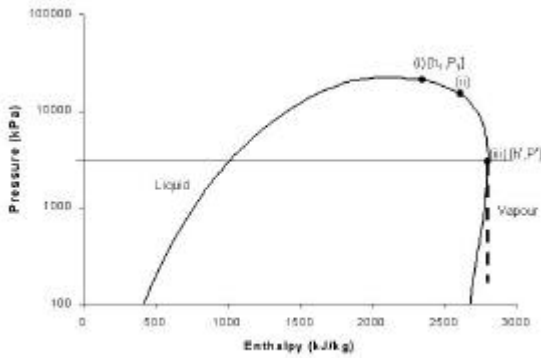


Figure 1. The pressure-enthalpy diagram for pure water. Within the two-phase zone saturated vapour ascends adiabatically [(i) to (ii)] and the specific enthalpy of vapour increases. Consequently some of the vapour condenses and the liquid so formed descends under gravity. This process occurs until the vapour reaches its maximum enthalpy at P^* [(iii)]. Above this point vapour ascends adiabatically to lower pressure regions and becomes superheated (dashed line). [The effect of dissolved gases such as CO_2 is not considered in this diagram].

We now develop a simple mathematical model to determine how the depth of the two-phase to single phase transition point varies with heat flux and pressure at depth.

Two-Phase Zone

Under steady state conditions within the two phase zone we can write the conservation of mass as

$$\frac{\partial}{\partial y} (m_l + m_v) = 0$$

where y denotes vertical direction, m denotes mass flux, suffix l denotes liquid and suffix v denotes vapour. We can also write the conservation of enthalpy as

$$\frac{\partial}{\partial y} (m_l h_l + m_v h_v) = 0$$

where h denotes the specific enthalpy.

The conservation of momentum is expressed in the form of Darcy's law. For simplicity, we use the concept of relative permeability and assume that relative permeability is proportional to saturation so that

$$m_l = -r_l \frac{K}{m_l} S \left(\frac{\partial P}{\partial y} + r_l g \right)$$

and

$$m_v = -r_v \frac{K}{m_v} (1 - S) \left(\frac{\partial P}{\partial y} + r_v g \right)$$

where r denotes density, K denotes permeability, S denotes liquid saturation, P denotes pressure and g denotes the acceleration due to gravity.

Finally, we assume that the properties of liquid and vapour are constant within the two-phase zone, with the exception of specific enthalpy. We approximate the specific enthalpy of liquid in the form

$$h_l = aP$$

where a is a constant. We approximate the specific enthalpy of vapour within the two-phase zone in a similar fashion so that

$$h_v = b - cP$$

where b and c are constants.

Single-Phase Zone

For pressures less than 3.1MPa, the ascending vapour no longer condenses and we therefore consider the fluid to be single phase vapour. We may write the conservation of mass as

$$\frac{\partial}{\partial y} (m_v) = 0$$

Similarly, the conservation of enthalpy may be written as

$$\frac{\partial}{\partial y} (m_v h_v) = h^* \frac{\partial}{\partial y} (m_v) = 0$$

where the specific enthalpy of vapour remains constant at h^* . Within the single phase zone, changes in density of the 'fluid' are governed by changes in density of the superheated vapour, unlike the two-phase zone where density changes were assumed to be dominated by changes in the saturation. We therefore assume that the density of vapour is proportional to the pressure so that we may write

$$m_v = -r_v^* \frac{P}{P^*} \frac{K}{m_v} (1 - S) \left(\frac{\partial P}{\partial y} + r_v g \right)$$

where * denotes conditions at the maximum enthalpy of vapour. Finally, we note that the single phase and two-phase zones are coupled through the conservation of mass and enthalpy flux at the transition point.

RESULTS

We first non-dimensionalise the governing equations. We consider a geothermal system of depth D , with a base pressure of P_o , and therefore non-dimensionalise depth y with respect to depth D so that

$$\hat{y} = \frac{y}{D}$$

and non-dimensionalise pressure P using the base pressure P_o so that

$$\hat{P} = \frac{P}{P_o}$$

We also non-dimensionalise the heat flux Q through the system based on the heat flux that would be transported through the system if vapour at maximum specific enthalpy was driven up through the reservoir with the pressure gradient P_o/D so that

$$\hat{Q} = \frac{Q m_v D}{r_v K P_o h^*}$$

We first consider an example where a geothermal system of 1000m vertical extent is supplied at depth with saturated fluid at a pressure equal to the hydrostatic pressure. In this case the pressure within the geothermal system decreases towards the surface as seen in figure 2.

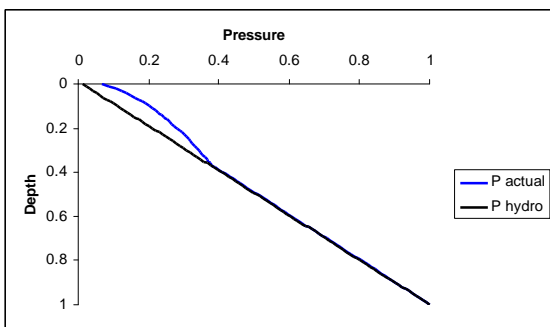


Figure 2. Pressure as a function of depth. Example shown is for geothermal system depth 1000m, base pressure = hydrostatic pressure + atmospheric and dimensionless heat flux = 0.5

The pressure gradient within the two-phase zone is sub-hydrostatic so that the condensate which forms descends to the base of the system. The pressure

gradient decreases at the transition point, and then gradually increases again as the superheated vapour becomes less dense nearer the surface.

Let us now consider how the dynamics of the system change as a function of the heat flux applied at depth. In figure 3 we show how the position of the transition point from two-phase to single phase conditions varies as a function of the heat flux supplied at depth.

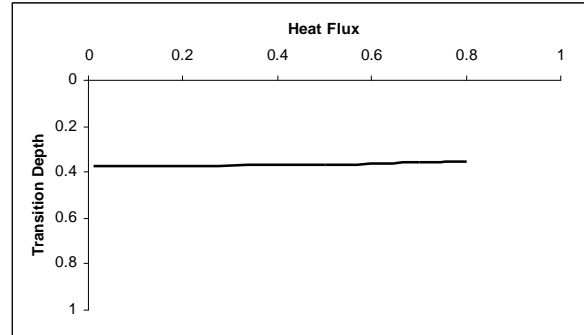


Figure 3. Depth of transition point from two-phase to single phase conditions.

In figure 3 single phase vapour overlies two-phase conditions. Depth is non-dimensionalised based on a 1000m deep system, and heat flux is non-dimensionalised as before. It is found that the vertical extent of the transition point increases slightly with applied heat flux. The pressure gradient within the two-phase zone is by definition sub-hydrostatic, thereby allowing liquid to descend (while vapour ascends). More convective heat flux can be accommodated through the two-phase zone if the circulating mass flux increases. Hence, more heat can be transported through the system if the pressure gradient within the two-phase zone weakens to enable a higher mass flux of descending liquid condensate.

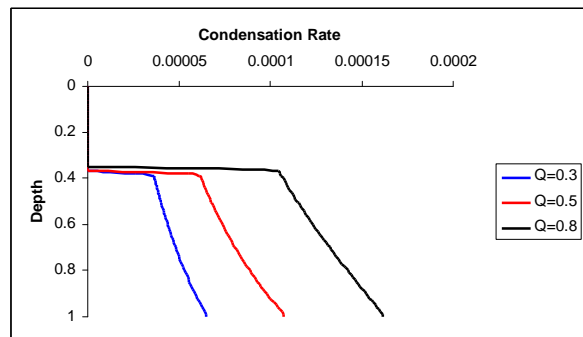


Figure 4. Rate of condensation as a function of depth for dimensionless heat fluxes of 0.3, 0.5 and 0.8. Condensation rates are expressed in the form $d/dy(m_v m D / K r_v P_o)$

Within the two-phase zone, liquid condensate is formed as vapour ascends. Since the circulating mass flux increases with heat flux, we find that the rates of

condensation within the two-phase zone increase with applied heat flux. This is shown in figure 4, where we show how the rate of formation of liquid (condensation rate) varies with depth for 3 different heat fluxes for the case in which the base pressure is hydrostatic pressure + atmospheric, and in which the system is 1000m deep. The height at which condensation ceases increases slightly with applied heat flux, in accordance with the observations of figure 3.

Finally, we note that the condensation within the two-phase zone can lead to dissolution of minerals such as silica and calcite. The dissolution of the minerals in the two-phase zone could therefore lead to an increase in permeability relative to the overlying rock containing superheated vapour. It is conceivable that the permeability contrast could increase with time, as illustrated schematically in figure 5.

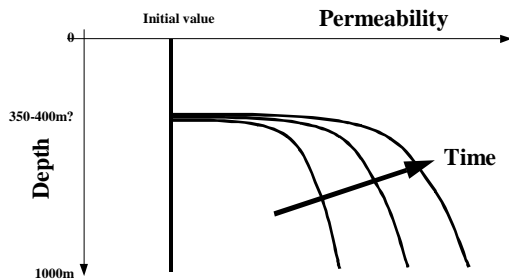


Figure 5. Schema of the potential evolution of the permeability structure within a geothermal reservoir.

CONCLUSIONS

There are a number of geothermal reservoirs around the world which exhibit a permeability contrast at or around a depth (below water table) of 300-500m. Examples include The Geysers in California (Ramey, 1968), Larderello in Italy and Kawah Kamojang (Dench, 1980) in Indonesia. Ramey (1968) described the The Geysers system in California as having a low permeability "cap" rock overlying the productive part of the reservoir. The depth of the transition point is extremely similar to the depth for

dissolution/no dissolution if the during the genesis of the reservoir, pressure was approximately hydrostatic at a depth > 500m. Such a concept is reasonable since geothermal systems are invariably supplied by meteoric water such that the pressure at the lateral extents of the system is close to hydro-static. We can therefore conclude that this process could have been responsible for the formation of the permeability contrasts which we see today (Ingebritsen and Sorey, 1988).

Future work will examine the dissolution process in more detail, and investigate how the system evolves when minerals are precipitated when any condensate re-boils at the base of the geothermal system.

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