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DOUBLE ADVECTIVE EFFECTS CONTROLLING LIQUID INJECTION IN GEOTHERMAL RESERVOIRS

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ABSTRACT

We examine the motion of liquid injected into a liquid dominated geothermal reservoir, focusing on the situation in which the injected liquid has different temperature and composition from the reservoir fluid. As a result of these differences, the injected liquid will typically be of different density to the reservoir fluid, and will therefore spread through the reservoir under gravity. Owing to the thermal inertia of porous rock, as the injected liquid spreads through the rock, the thermal front lags behind the actual fluid front associated with the injected liquid. As a result, the density of the injected fluid changes across the thermal front: fluid ahead of the front has density different from that in the reservoir only as a result of differences in composition; fluid behind the front has density which is different owing to contrasts in temperature and composition. This leads to a change in the structure of the current across the thermal front, and we examine a range of different situations which may develop depending on the initial temperature and compositional contrasts.

INTRODUCTION

Liquid injection into geothermal reservoirs typically involves fluids whose composition and temperature differ from that in the reservoir. This can lead to an important role of the gravitational or buoyancy force, in additional to the applied pressure, in driving the fluid through the reservoir. Previous studies have examined the controls on the gravitational spreading of liquid injected into geothermal systems (Woods, 1998a; Woods, 1999), in the situation in which the density contrast between the reservoir fluid and the injected fluid is constant. In that situation, it has been shown that the fluid spreads in a self-similar fashion through the reservoir. Solutions have been developed for motion along sloping impermeable layers in the reservoir issuing from a point source as well as for radially spreading currents issuing from a central well along a nearly horizontal impermeable boundary.

Other work has considered the effect of fluid-rock reactions on the spreading rate and current morphology of fluid migrating under gravity through the reservoir (Raw and Woods, 2000). By extending the earlier models of gravity currents, more involved model solutions have shown how the current can develop a double structure: injected fluid advances from the source through the reacted porous layer towards the reaction front. At the reaction front, the permeability changes due to reaction, and beyond this front the injected, but already-reacted fluid spreads through the original reservoir rock. In another study, the motion of vaporizing gravity currents has also been examined, with fluid at the advancing surface of the current partially boiling as it enters superheated rock (Woods, 1998b).

DENSITY EVOLUTION

In all these studies, the density of the injected fluid has been assumed to be fixed. However, owing to the thermal inertia of fluid migrating through a porous rock, the density may change across the thermal front, leading to a range of previously unrecognized current behaviours. To illustrate the different possibilities, it is useful to consider a simple model in which the density of the reservoir fluid is given by

$$\rho = \rho_o\left(1-\alpha\left(T-T_o\right)+\beta\left(C-C_o\right)\right) \qquad (1)$$

where the density ρ, relative to a reference density ρ_o defined at temperature T_o and concentration C_o is assumed to decrease with temperature, with thermal expansion coefficient α and increase with the concentration of dissolved mineral or salt with solutal expansion coefficient β.

Coupling equation (1) with the result that for advectively controlled heat transfer through a porous layer, an internal thermal boundary layer typically develops, across which the temperature changes from the injection temperature to the original reservoir temperature, several transitions in flow density become evident.

(1) If the concentration of the injected fluid exceeds that of the reservoir fluid, then the injected fluid will eventually become dense relative to the reservoir fluid, once it has advanced ahead of the thermal front. However, initially, the injected fluid may
  (a) be colder than the reservoir fluid, in which case the injected fluid will warm up as it moves into the reservoir, and hence the density excess over the reservoir fluid will decrease
  (b) be warmer than the reservoir fluid, in which case the injected fluid may initially either be (i) less dense than the reservoir fluid (for very hot injectate – see analogue expt. Fig. 4) or (ii) more dense than the reservoir fluid, but in both cases the density of the injected fluid increases to a value greater than the original reservoir fluid as it passes across the thermal front.

(2) If the concentration of the injected fluid is smaller than the reservoir fluid then a complementary set of regimes exist. Now, the injected fluid will ultimately become less dense than the reservoir fluid, once it has passed the thermal front. But the fluid may initially either
  (a) be warmer than the reservoir fluid, in which case the injected fluid is less dense than the reservoir fluid (see fig 3)
  (b) be colder than the reservoir fluid, in which case the injected fluid may (i) initially be denser than the reservoir fluid (very cold injectate) or (ii) less dense than the reservoir fluid (cold injectate).

These different regimes are illustrated in figure 1 below

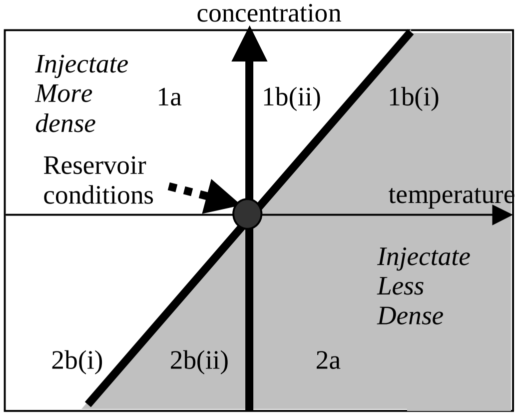

Figure 1 – The different fluid density regimes as injection temperature and composition vary. Shaded area denotes less dense injectate

FLOW REGIMES

Given the different regimes in figure 1, we expect a number of different flow scenarios might develop as liquid is injected from a central well and spreads out under gravity. For simplicity we focus on case 2, in which the injected liquid eventually becomes less dense than the reservoir fluid, owing to the smaller concentration of dissolved mineral in the injected liquid.

For case 2a, the hot injected fluid always remains less dense than the reservoir fluid, and we anticipate that a buoyant current will spread along the upper boundary of the reservoir. This current cools and becomes relatively dense as it spreads and will therefore have the generic morphology of figure 2a below. For case 2bii, the current is again always buoyant, but now becomes more buoyant as the relatively cool injected fluid spreads across the thermal boundary layer and warms up. The flow is therefore expected to the have the different morphology of fig 2bii below. Finally, in case 2bi, the current is initially relatively dense, since the injected fluid is sufficiently cool that this dominates the smaller concentration of dissolved solute than is present in the resevoir fluid. However, as the current warms up, the injected liquid becomes less dense and rises to the top of the reservoir (fig 2bi).

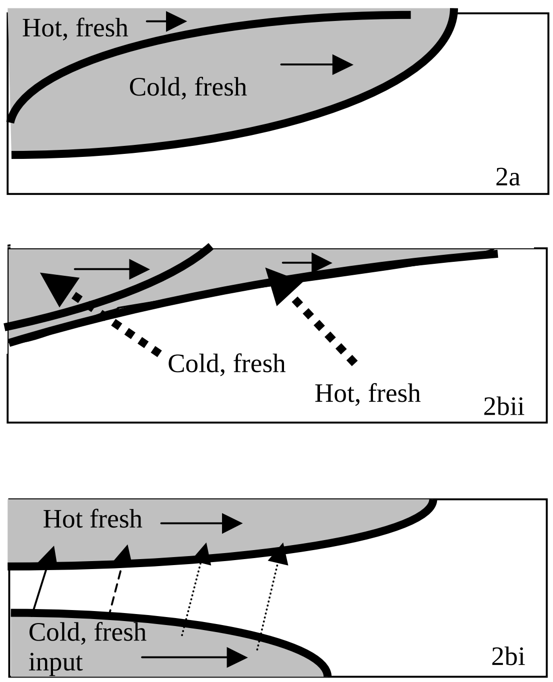

Figure 2 a, bii, bi Illustration of the general morphology of currents which become (a) more dense as the fluid moves across the thermal front and cools, and hence spread more slowly; (bii) less dense as they move across the thermal front and hence spread more rapidly; and (bi) illustrate a reversal in *density as the fluid heats up, and becomes less dense, giving a double current structure.*

In order to model the flows illustrated in regimes 2a and 2b(ii) , one can follow the approach of Raw and Woods (2000), but replacing the reaction front with the thermal front, and instead of modelling the change in permeability we account for the change in buoyancy across this front, assuming a narrow thermal boundary layer, as will typically be the case (Phillips, 1991). These solutions will be presented in more detail elsewhere. The key result is that for constant injection rate, the current spreads laterally through the system so that the current length increases at a rate proportional to time$^{2/3}$, while the current depth evolves at a rate proportional to time$^{1/3}$.

EXPERIMENTAL STUDY

Here we now report on some new laboratory experiments designed to illustrate the key ideas of this model for injection. For simplicity, we use a bead pack of dimension 4 cm x 50 cm x 30 cm, and fill this to a depth of about 20 cm with glass beads of 3mm diameter. The beads are then saturated with fresh or saline water. A mixture of hot, and either fresh or saline solution is then prepared and slowly injected at the top centre of the bead-pack.

Two sets of experiments are reported here. First, (figure 3) an experiment in which the injected liquid is relatively hot compared to the fluid in the layer, but of the same composition, so that the density of the current is smaller than the original fluid in the bead pack (the boundary between cases 1b(i) and 2a; figure 1). In this case, as the fluid spreads through the reservoir, the fluid heats up the bead pack near the source, and then moves across the thermal boundary layer into the region with the original bead pack temperature. The density of the injected fluid then becomes very similar to that of the original fluid and the motion slows considerably, with the current deepening as it spreads. Dark dye added to the injected fluid mid-way through the experiment, shows the fluid initially moving along the top of the layer, in the region where the bead pack has been heated, but then, as the fluid passes through the thermal front, it loses its buoyancy and deepens.

The second experiment, which we illustrate in figure 4, corresponds to the case in which the fluid injected to the top of the bead pack is hot and saline relative to the clear fluid in the bead pack (case 1bi, fig 1). The current is initially less dense than the host fluid, and therefore spreads out on the top boundary.

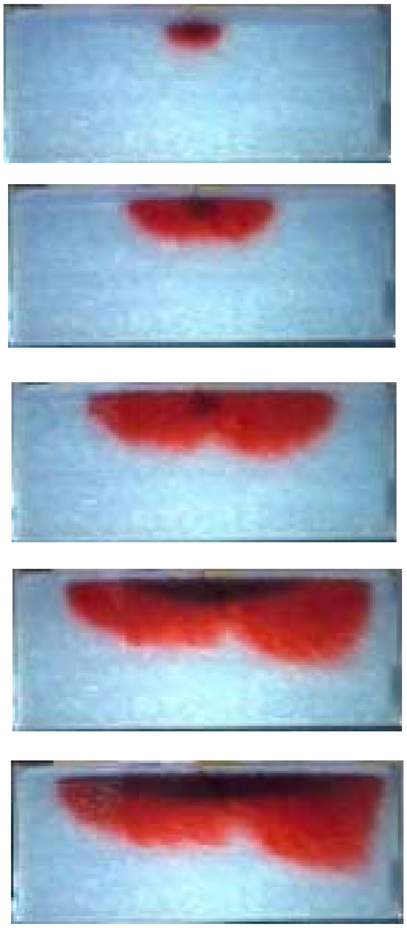

Figure 3. Injection of hot liquid into a bead pack filled with cold liquid. This corresponds to injection at conditions transitional between regimes 2a and 2b(ii), where the fluid is less dense than the host fluid purely due to the initial temperature contrast. The dye may be seen in the later figures showing the fluid spreading along the upper boundary before passing through the thermal boundary layer and the temperature adjusting to that of the original layer.

However, as the fluid passes through the thermal boundary layer and cools, the saline injectate becomes relatively dense and descends to the base of the system, where it spreads out as a dense saline gravity current on the base of the reservoir. Again, at some point in the experiment, the injected fluid was dyed, in order to visualise this process. It can be seen that this fluid initially spreads along the top of the bead pack, within the region heated by the fluid injected earlier in the experiment, but then descends as the fluid passes through the thermal boundary layer.

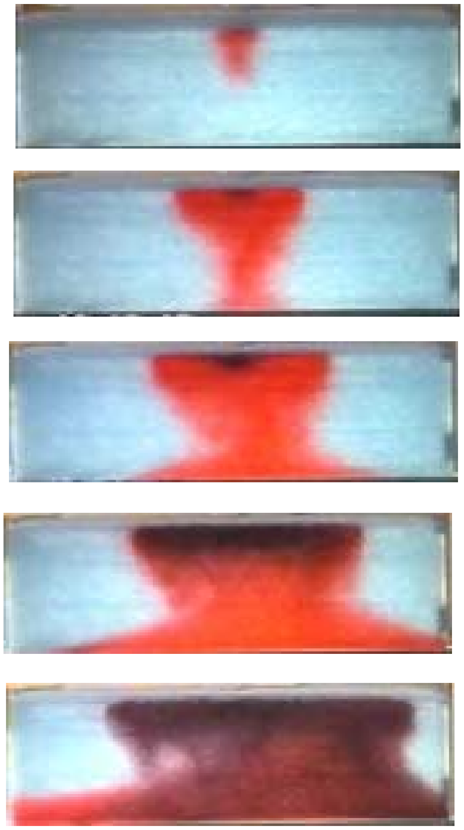

Figure 4: Illustration of an experiment in regime 1bi, in which an initially buoyant current (very hot but salty) becomes dense as it cools and the salinity begins to dominate the thermal effects on density.

CONCLUSIONS AND DISCUSSION

We have presented a simple model of injection of fluid, whose density varies both due to temperature and salinity , into a geothermal reservoir. This has identified a series of different situations in which the fluid injected into the reservoir may be either less dense or more dense than the fluid originally in the reservoir. It has also identified how that density of the injected fluid may change relative to the fluid in the reservoir, as a result of the thermal inertia, whereby the injected fluid travels more rapidly than the thermal flux associated with the fluid.

The results may be of interest in the geothermal context in terms of attempts to sweep a greater fraction of the hot reservoir rock with injected fluid. If the flow front density can be designed to evolve to be close to that of the host fluid, then the front will spread through the reservoir as a relatively deep current (figure 3). This scenario contrasts with a current in which there is a significant difference in density owing to compositional differences between the injected and resevoir fluids. In that case, unless the layer of permeable reservoir rock is sufficiently thin, the current is likely to be strongly controlled by gravity, and the injected fluid may only sweep through a fraction of the reservoir.

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