

THERMOHALINE CONVECTIVE MIXING AT A BRINE INTERFACE

C.M. Oldenburg and K. Pruess

Earth Sciences Division
Berkeley Lab
Berkeley, CA, USA, 94720
e-mail: cmoldenburg@lbl.gov

ABSTRACT

Thermohaline convection in hypersaline geothermal systems is driven by heat and salinity effects on liquid density. Thermal retardation in porous media causes thermal and brine plumes to separate, leading to segregation and mixing phenomena not observed in viscous liquid systems. We performed two-dimensional numerical simulations of thermohaline convection to investigate mixing effects at a gravitationally stable brine interface such as that inferred to exist in the Salton Sea Geothermal System. Using plausible density and viscosity models that consider the influence of heat and salinity on liquid properties, simulations show that thermal retardation subtly enhances convective mixing by allowing the thermal and salinity effects on density to be expressed independently upon plume separation. Permeability anisotropy, where vertical permeability is smaller than horizontal permeability, and brine viscosity inhibit mixing.

INTRODUCTION

Natural convection in liquid-dominated hypersaline geothermal systems is called thermohaline convection because it is driven by thermal and solute effects on liquid density. Because heat and salt diffuse through liquid water at different rates, thermohaline convection is double-diffusive convection (e.g., Veronis, 1965). However, in porous media systems, where heat interacts with the solid grains of the matrix, thermohaline double-diffusive systems evolve to become double-advective once convection begins since heat moves at approximately the Darcy velocity whereas salt moves with the liquid at the pore velocity (Phillips, 1991; Oldenburg and Pruess, 1998). The slower transport of heat relative to solute is called thermal retardation.

Thermal retardation and the associated unmixing of heat and brine plumes in porous media gives rise to segregation and mixing phenomena not observed in viscous liquid systems. For example, thermal retardation causes density lids to form on upward moving brine plumes as the brine front moves ahead of the thermal front, while in descending plumes the thermal and brine plumes can separate completely (Oldenburg and Pruess, 1999). When heat and brine separate during transient flows in thermohaline systems, the density effects due to heat and salinity act independently leading to larger local density contrasts. The effect of larger local density contrasts is to increase convective vigor and thereby enhance mixing.

Thermohaline convection and associated double-advective effects are expected to be important in hypersaline geothermal systems such as the Salton Sea Geothermal System (SSGS) located in the Imperial Valley of southern California. In fact, data from the SSGS suggest the presence of a sharp interface between hot hypersaline brine and cooler, less saline fluids. The formation of layers and stratification in the SSGS has been attributed to double-diffusive convection (Fournier, 1990). Numerical experiments suggest that layering is favored by permeability anisotropy where vertical permeability is less than horizontal permeability (Oldenburg and Pruess, 1998). The question arises as to how a sharp brine interface can persist in the presence of thermohaline convective mixing.

In this study, we investigate by two-dimensional numerical simulations the convective mixing at a gravitationally stable brine interface. We report on the role played by double-advective effects, permeability anisotropy, and viscosity variation on the maintenance of sharp brine interfaces such as that observed at the SSGS.

PRIOR WORK

The literature for porous media double-diffusive convection is sparse relative to that of viscous

liquids. Nevertheless, significant prior work has been carried out on porous media including stability analyses (e.g., Nield, 1968; Poulikakos, 1986), laboratory investigations (Griffiths, 1981; Cooper *et al.*, 1997), and numerical studies (e.g., Rosenberg and Spera, 1990; Schoofs *et al.*, 1998). Prior numerical studies have investigated the effects of classical dimensionless parameters such as the thermal and solutal Rayleigh numbers, ratios of diffusivities (Lewis numbers), viscosity ratios, permeability anisotropy, as well as initial and boundary conditions. Although the role played by porosity in causing thermal retardation in porous media thermohaline convection was discussed by Phillips (1991), it is only recently that the resulting double-advective effects, which are particularly important in low porosity formations, have been investigated explicitly (Oldenburg and Pruess, 1998; 1999).

The conceptual model of the SSGS that has emerged over years of investigation includes magma moving into space created by offsets in the San Andreas fault system with heating of the brine and groundwater in the basin-fill sediments (e.g., Younker *et al.*, 1982; Newmark *et al.*, 1986; Fournier, 1990). A sharp brine interface exists at depth where hot ($T = 300$ °C) hypersaline brines underlie less saline and cooler ($T < 260$ °C) brines (Williams, 1988; Williams and McKibben, 1989). The temperature gradients are smaller at depth and larger higher in the system. Salinity variations are approximately correlated with temperature, creating overall small density variations (Helgeson, 1968). The smaller temperature gradients deep in the system point toward the importance of mixing by thermohaline convection. The maintenance and evolution of the sharp brine interface in the presence of thermohaline convection is the focus of the present study.

NATURAL CONVECTION EQUATIONS

Starting with Darcy's Law for flow through porous media,

$$\mathbf{u} = -\frac{k}{\mu}(\nabla P + \rho \mathbf{g}) \quad (1),$$

the partial differential equations governing porous media thermohaline convection can be written for the aqueous mixture, solute, and heat as

$$\phi \frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{u}) \quad (2),$$

$$\phi \frac{\partial \rho X^k}{\partial t} = -\nabla \cdot (\rho \mathbf{u} X^k) + \nabla \cdot (\bar{\mathbf{D}}^k \nabla X^k) \quad (3),$$

and

$$\phi \frac{\partial}{\partial t} \left(\rho C T + \frac{(1-\phi)}{\phi} \rho_R C_R T \right) = -\nabla \cdot (\rho C \mathbf{u} T) + \nabla \cdot (\bar{\mathbf{D}}_h \nabla T) \quad (4)$$

where \mathbf{u} is the Darcy velocity and the full dispersive flux for heat is included in $\bar{\mathbf{D}}_h$ (Bear, 1988).

As seen in Eq. 1, permeability and its anisotropy, as well as viscosity, are important variables controlling convection along with the density gradient.

Another important control is exerted by porosity, as shown in Eqs. 3 and 4. Porosity causes heat transport to be retarded due to the heat exchange between the fluid and the solid grains. The effective thermal retardation factor is given by the ratio of the total heat capacity of the rock-fluid mixture to the heat capacity of the fluid (Bodvarsson, 1972),

$$R^h = 1 + \frac{(1-\phi) \rho_R C_R}{\phi \rho C} \quad (5).$$

For a given Darcy velocity u , pore velocity is u/ϕ , which means that the velocity of the advective thermal front is

$$v_{th} = \frac{u}{\phi R^h} = u \frac{\rho C}{\phi \rho C + (1-\phi) \rho_R C_R} \quad (6)$$

(e.g., Grant *et al.*, 1982). Thermal retardation can become very large as porosity becomes small. With the properties $\phi = 0.1$, $\rho_R = 2650 \text{ kg m}^{-3}$, $C_R = 1000 \text{ J kg}^{-1} \text{ K}^{-1}$, $C = 4184 \text{ J kg}^{-1} \text{ K}^{-1}$, the retardation factor will be $R^h = 6.7$. For typical properties of a permeable aquifer, the thermal front will move at approximately the Darcy velocity, or in this case $\sim 1/7$ the speed of the solute front which moves at the pore velocity, u/ϕ . Thermal retardation effects are transient and do not affect steady-state systems. In a coupled system where heat and brine affect liquid density, the difference in effective transport rates of heat and brine will lead to increased local density contrasts.

NUMERICAL EXPERIMENT

Model

In order to investigate the convective mixing at a brine interface in a hypersaline geothermal system, we carried out numerical simulations of an idealized two-dimensional system consisting of a hot brine underlying cooler, less saline water. We used the integral finite difference simulator TOUGH2 (Pruess, 1991a; Pruess *et al.*, 1999) to solve the strongly coupled system of equations for thermohaline convection. TOUGH2 uses a fully coupled solution

technique and residual-based convergence criterion that is efficient for strongly coupled flow and transport. Transport of heat and brine is by advection and diffusion, with dispersive effects neglected.

We used the previously developed density model based on EOS7 (Pruess, 1991b) that considers the effects on brine density of a mixed brine component consisting of NaCl and CaCl₂ as well as heat (Oldenburg and Pruess, 1998). The density model is shown in Figure 1. Along with data from the SSGS from Williams (1988), we show two large open circles with a connecting line representing fluids from the two model layers showing the variation in density is approximately 5%. A schematic of the domain and boundary conditions is presented in Figure 2, with specific parameters shown in Table 1. Note that for one simulation the porosity will be set to unity, a case chosen to highlight convective dynamics in the case where there is no thermal retardation. We also consider viscosity variation to be a function of brine mass fraction using a model after Herbert *et al.* (1988); see also Oldenburg and Pruess (1998).

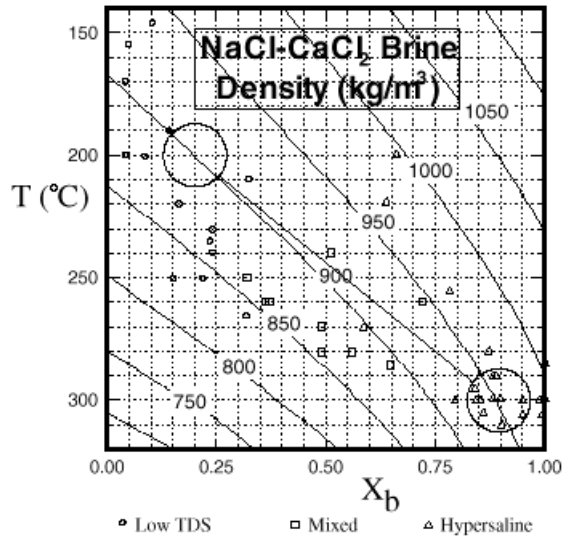


Figure 1. Density model with temperature and brine mass fraction of the two layers shown by the large open circles and connecting line.

The initial condition for the simulations described below is shown in Figure 3 and consists of a stably stratified system with incipient convection beginning at the interface and with heating (Q) at the bottom. The value of $Q = 0.70 \text{ W m}^{-2}$ was chosen based on Fourier's law and the temperature gradient in the caprock and upper part of the SSGS reservoir of $0.35 \text{ }^\circ\text{C m}^{-1}$ (e.g., Fournier, 1990). In order to destabilize the system slightly and promote convection, Q at the bottom was set to alternate between 0.70 and 0.77 W m^{-2} every two gridblocks, with the two-dimensional grid discretized into square gridblocks 100 m on a side. The initial condition shown in Figure 3 was

generated by letting the system evolve for 150 years from the conditions shown in Figure 2. Note that the thermal boundary layer has already established itself by conduction causing heating above the brine interface and cooling below. Note that there is also a brine boundary layer that is thinner than the thermal boundary layer. The contrast between the thickness of these two boundary layers shows the effect of double-diffusion, namely that heat diffuses faster than brine. We use this gravitationally stable incipiently convecting system as the initial condition for a series of simulations that demonstrate the role of properties such as porosity, permeability, and viscosity.

Table 1. Parameters for thermohaline mixing.

property	value	units
<i>Upper Layer</i>		
initial temperature (T)	200	$^\circ\text{C}$
initial brine mass fraction (X_b)	0.20	-
initial density (ρ)	~ 920	kg m^{-3}
<i>Lower Layer</i>		
initial temperature (T)	300	$^\circ\text{C}$
initial brine mass fraction (X_b)	0.90	-
initial density (ρ)	~ 960	kg m^{-3}
<i>Both Layers</i>		
porosity	0.15/1.0	-
Y-direction permeability (k_Y)	5.0×10^{-12}	m^2
Z-direction permeability (k_Z)	5.0×10^{-13}	m^2
molecular diffusivity (d)	1.0×10^{-8}	$\text{m}^2 \text{ s}^{-1}$
formation conductivity (K)	1.8	$\text{J s}^{-1} \text{ m}^{-1} \text{ K}^{-1}$
tortuosity (τ)	1.0	-
heat capacity of rock (C_R)	1000	$\text{J kg}^{-1} \text{ K}^{-1}$
density of rock (ρ_R)	2650	kg m^{-3}
gravity (g)	9.81	m s^{-2}

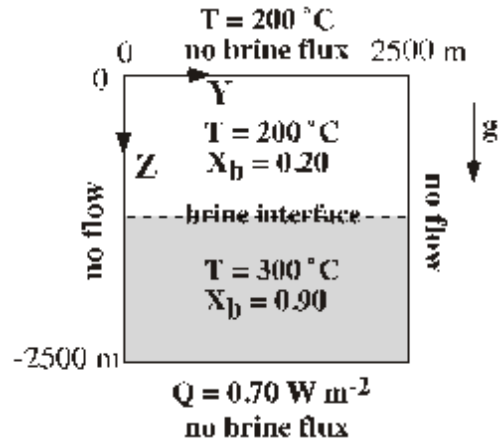


Figure 2. Domain and boundary conditions for the brine interface mixing problem.

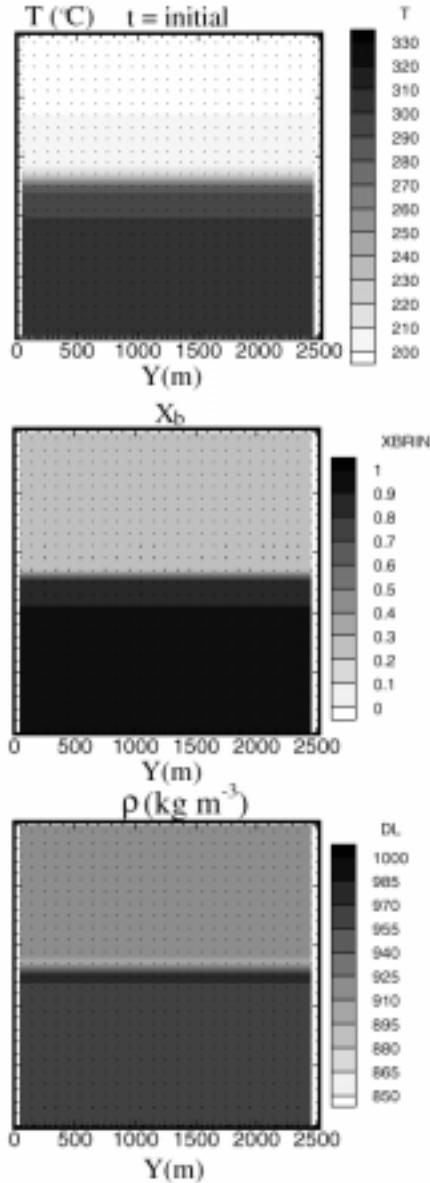


Figure 3. Initial conditions for the brine interface mixing simulations.

Results

We present in Figure 4 the evolution of the temperature, brine mass fraction, and density fields at $t = 500$ and 1000 years for the case of $\phi = 0.15$, $k_Y = 5 \times 10^{-12} \text{ m}^2$, $k_Z = 5 \times 10^{-13} \text{ m}^2$ and full viscosity variation due to heat and salinity. We see in Figure 4 that convection is occurring in both layers. The degree of mixing at the brine interface can be seen by the thickness of the thermal and brine mixing zones near the interface. The thermal mixing zone above and below the interface is larger than the brine mixing zone, a feature that allows convection to occur in the layers above and below the interface. This is a fundamental feature of double-diffusive convection in viscous liquids and porous media, namely the generation of local buoyancy in overall

stably stratified systems by differential growth of boundary layers. The main feature to note in Figure 4 is the overall stability of the brine interface. Even after 1000 years in the simulation, the interface

persists with convection occurring in the two layers. The density variation between the layers creates an effective lid on the system, limiting upward transport of heat and brine to conduction across thermal boundary layers near the interface.

To show the subtle effects of thermal retardation, we present in Figure 5 a simulation with $\phi = 1.0$, a non-physical case chosen to contrast with the prior case that included thermal retardation. Note in Figure 5 that mixing at the interface is reduced relative to the $\phi = 0.15$ case shown in Figure 4. The reason for this is that with no thermal retardation, the thermal and brine plumes do not separate, but instead move nearly in lockstep, with transport differing only by relative differences in diffusion. The result is smaller local density differences and therefore slower overall mixing between the two layers when double-advective effects are suppressed. The point of this example is simply to demonstrate that convective vigor is reduced when the porosity is large. In general, it appears that low porosity promotes mixing by thermohaline convection due to greater thermal retardation and the associated stronger convection.

The effects of permeability anisotropy are shown in Figure 6 where we present the case of mixing at the interface for $k_Y = k_Z = 5 \times 10^{-13} \text{ m}^2$ with $\phi = 0.15$. The figure shows that when vertical and horizontal permeability are equal, vertical flow becomes more dominant relative to horizontal flow. The effect of stronger vertical motions is to increase mixing at the interface.

The effects of brine mass fraction dependence on viscosity were investigated by setting the coefficients of viscosity variation to very small numbers to make the brine viscosity equal to that of pure water independent of brine mass fraction. As shown in Figure 7, we observe at $t = 500$ years slightly greater mixing than the variable viscosity case (Figure 4) due to the overall smaller viscosity and lack of viscosity contrast. By $t = 1000$ years, the brine interface was no longer present in the constant viscosity simulation. While further investigation of viscosity effects is warranted, we tentatively conclude that the greater viscosity of brine is an important property of thermohaline systems that will act to inhibit the mixing across stable brine interfaces.

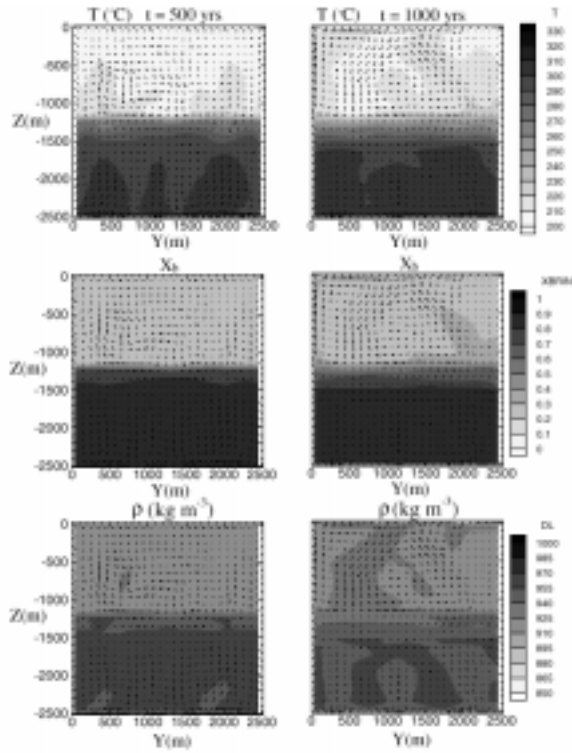


Figure 4. Temperature, brine mass fraction, and density at $t = 500$ and 1000 years for the case where $\phi = 0.15$.

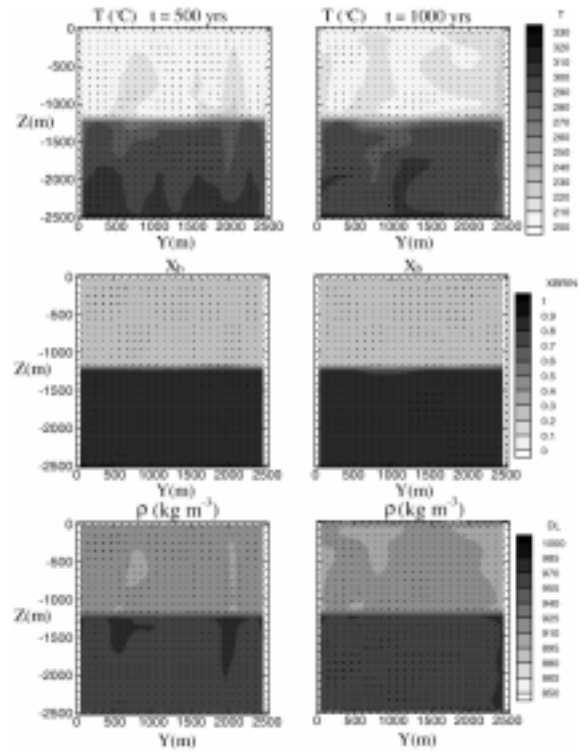


Figure 5. Temperature, brine mass fraction, and density at $t = 500$ and 1000 years for the case where $\phi = 1.0$ (i.e., no thermal retardation).

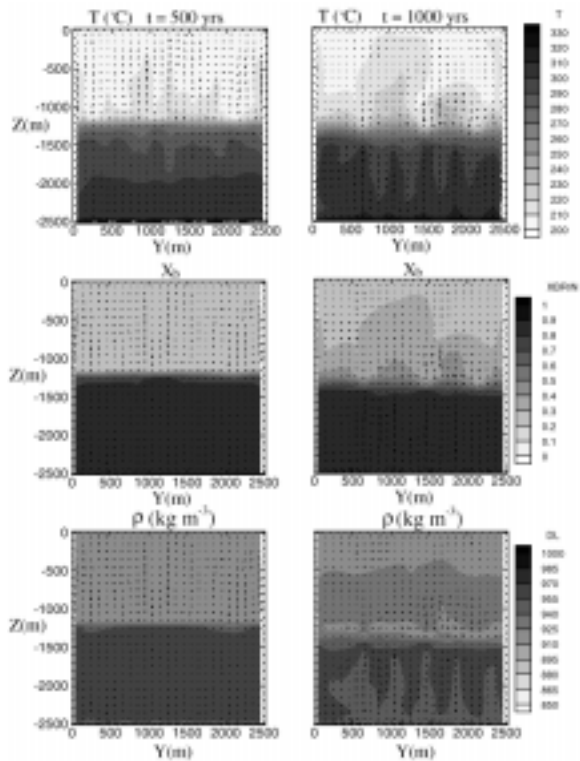


Figure 6. Temperature, brine mass fraction, and density at $t = 500$ and 1000 years for the case where $k_Y = k_Z = 5 \times 10^{-13} \text{ m}^2$.

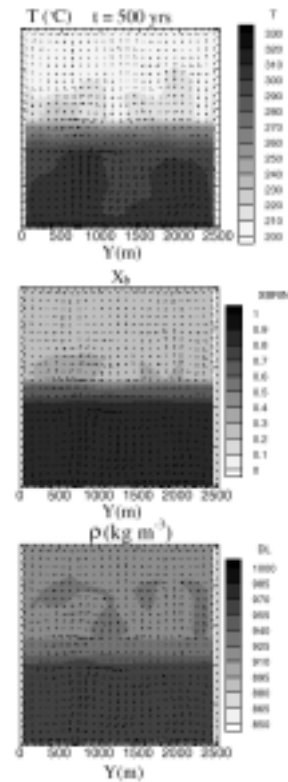


Figure 7. Temperature, brine mass fraction, and density at $t = 500$ years for the case where viscosity variations with brine mass fraction have been neglected.

A summary figure showing vertical profiles of brine mass fraction through the center of the domain is presented in Figure 8 for the cases shown in Figures 3–6 at $t = 1000$ years. Note that the greatest mixing has occurred for the case of isotropic permeability, while very little mixing happened for the case of unit porosity, i.e., no thermal retardation.

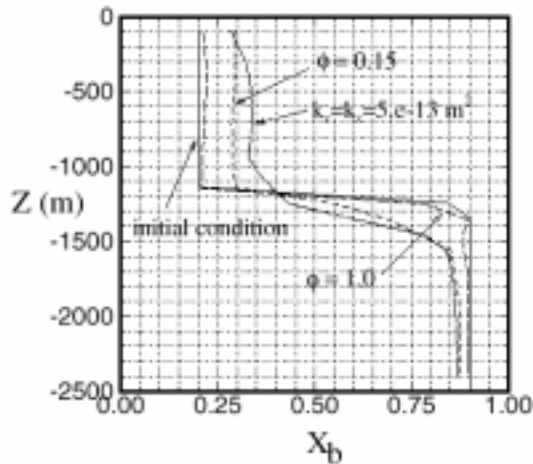


Figure 8. Vertical profile of brine mass fraction at the initial condition and at $t = 1000$ years for the $\phi = 0.15$, $\phi = 1.0$, and isotropic permeability cases.

DISCUSSION AND CONCLUSIONS

We have investigated the thermohaline convective mixing at a brine interface modeled after the interface at the SSGS. The large density contrast (~5%) between hot hypersaline brines and cooler lower-salinity waters creates a gravitationally stable brine interface. Around the interface, thermohaline convection develops due to heating above the interface and cooling below it. Our simulations show that the double-advective effects arising from the slower transport of heat relative to brine in porous media enhance convective mixing. The reason for this enhancement is that heat and brine can separate in thermohaline convection in porous media, and upon separation give rise to larger local density gradients that in turn create more vigorous convection. Despite the increased mixing due to thermal retardation, the layer is overall quite stable and persistent, as shown in our simulations going out 1000 years.

Permeability anisotropy where $k_y > k_z$ decreases convective mixing. For sediments at the SSGS, the vertical permeability of the matrix may be 10 or more times smaller than the horizontal permeability. Thus we expect permeability anisotropy to inhibit mixing and favor the maintenance of the sharp brine interface. The effects of fracturing on the stability of the interface remain to be investigated.

Brine viscosity was also observed to inhibit convective mixing at the brine interface. For the SSGS, the brine can be assumed to be more viscous than less saline liquids at the same temperature and pressure and thus variable viscosity will favor maintenance of the brine interface. Future studies may be carried out to investigate thermal retardation and the associated faster mixing and variable viscosity effects that inhibit mixing.

In summary, simulations show that a stable brine interface such as that at the SSGS is persistent and acts as a barrier to prevent upward convective flows and mixing of fluids of different temperature and salinity. Thermal retardation and its tendency to pull heat and brine plumes apart subtly enhances convective mixing. Permeability anisotropy and variable viscosity inferred for the SSGS both inhibit mixing and favor the maintenance of a stable brine interface.

Acknowledgments

We thank Stefan Finsterle and Marcelo Lippmann for their careful reviews. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Geothermal and Wind Technologies, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

- Bear, J., *Dynamics of Fluids in Porous Media*, Dover, 764 pp., 1988.
- Bodvarsson, G., Thermal problems in the siting of reinjection wells, *Geothermics*, 1(2), 63–66, 1972.
- Cooper, C.A., R.J. Glass, and S.W. Tyler, Experimental investigation of the stability boundary for double-diffusive finger convection in a Hele-Shaw cell, *Water Resour. Res.*, 33(4), 517–526, 1997.
- Fournier, R.O., Double-diffusive convection in geothermal systems: The Salton Sea, California, geothermal system as a likely candidate, *Geothermics*, 19(6), 481–496, 1990.
- Grant, M.A., I.G. Donaldson, and P.F. Bixley, *Geothermal Reservoir Engineering*, Academic Press, 369 pp., 1982.
- Griffiths, R.W., Layered double-diffusive convection in porous media, *J. Fluid Mech.*, 102, 221–248, 1981.

- Helgeson, H.C., Geologic and thermodynamic characteristics of the Salton Sea geothermal system, *Am. J. Sci.*, 266, 129–166, 1968.
- Herbert, A.W., C.P. Jackson, and D.A. Lever, Coupled groundwater flow and solute transport with fluid density strongly dependent on concentration, *Water Resour. Res.*, 24(10), 1781–1795, 1988.
- Newmark, R.L., P.W. Kasameyer, L.W. Younker, and P.C. Lysne, Research drilling at the Salton Sea Geothermal Field, California: The shallow thermal gradient project, *Trans. of the Am. Geophys. Union EOS*, 67(39), 698–707, 1986.
- Nield, D.A., Onset of thermohaline convection in a porous medium, *Water Resour. Res.*, 4(3), 553–560, 1968.
- Oldenburg, C.M., and K. Pruess, Layered thermohaline convection in hypersaline geothermal systems, *Transport in Porous Media*, 33, 29–63, 1998.
- Oldenburg, C.M., and K. Pruess, Plume separation by transient thermohaline convection in porous media, *Geophys. Res. Letts.*, 26(19), 2997–3000, 1999.
- Phillips, O.M., *Flow and Reactions in Permeable Rocks*, Cambridge University Press, Cambridge UK, 285 pp., 1991.
- Poulikakos, D., Double diffusive convection in a horizontal sparsely packed porous layer, *Int. Comm. Heat Mass Trans.*, 13, 587–598, 1986.
- Pruess, K., TOUGH2 - A General Purpose Numerical Simulator for Multiphase Fluid and Heat Flow, *Lawrence Berkeley Laboratory Report LBL-29400*, May 1991a.
- Pruess, K., EOS7, An Equation-Of-State Module for the TOUGH2 Simulator for Two-Phase Flow of Saline Water and Air, *Lawrence Berkeley Laboratory Report LBL-31114*, August 1991b.
- Pruess, K., C. Oldenburg, and G. Moridis, TOUGH2 User's Guide, *Lawrence Berkeley National Laboratory Report LBNL-43134*, November 1999.
- Rosenberg, N.D., and Spera, F.J., Role of anisotropic and/or layered permeability in hydrothermal convection, *Geophys. Res. Letts.*, 17(3), 235–238, 1990.
- Schoofs, S., R. A. Trompert, and U. Hansen, The formation and evolution of layered structures in porous media, *J. Geophys. Res.*, 103(B9), 20,843–20,858, 1998.
- Veronis, G., On finite amplitude instability in thermohaline convection, *J. Marine Res.*, 23, 1–17, 1965.
- Williams, A.E., Delineation of a brine interface in the Salton Sea Geothermal System, California, *Geotherm. Resour. Council, Trans.*, 12, 151–157, 1988.
- Williams, A.E., and M.A. McKibben, A brine interface in the Salton Sea geothermal system, California: fluid geochemical and isotopic characteristics, *Geochem. et Cosmochim. Acta*, 53, 1905–1920, 1989.
- Younker, L.W., P.W. Kasameyer, and J.D. Tewhey, Geological, geophysical, and thermal characteristics of the Salton Sea Geothermal Field, California, *J. Volcanol. Geotherm. Res.*, 12, 221–258, 1982.