

DOUBLE-DIFFUSIVE CONVECTION AS A MECHANISM FOR TRANSFERRING HEAT AND MASS
WITHIN THE SALTON SEA GEOTHERMAL BRINE

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ABSTRACT

H. C. Helgeson noted in 1968 that the salinity of the brine in the geothermal reservoir within the Salton Sea geothermal system generally increases from the top to the bottom and from the center to the sides. He also noted that pressure measurements at perforations in cased wells seemed to indicate that the formation fluids at the depths of production have a specific density about equal to 1, and that hot concentrated brines apparently exist in pressure equilibrium with comparatively cold dilute pore waters in the surrounding rocks. Since 1968 there have been no published reports that dispute these observations. However, a very high heat flux through the top of the system seems to require a substantial component of convective transfer of heat beneath an impermeable cap, whereas the apparent salinity gradient with depth seems to require little or no free convection of brine. This paradox may be resolved if double-diffusive convection is the main process that controls the depth-temperature-salinity relations. Such convection provides a mechanism for transferring heat from the bottom to the top of the hydrothermal system while maintaining vertical and horizontal salinity gradients--densities remaining close to unity.

In 1981, Griffiths showed experimentally that layered double-diffusive convection cells may develop in porous media when hot saline waters underlie more dilute cooler waters. However, nagging questions remain about whether fluid densities within the Salton Sea geothermal system really adjust to unity in response to changing temperature and salinity at depths greater than about 1 km. The State 2-14 well, the Salton Sea Scientific Drill Hole, has provided one high-quality data point for a depth interval of 1,865-1,877 m, where the temperature is about 305°C. The calculated density of the pre-flashed reservoir fluid sampled from that depth is 1.0008 ± 0.0023 .

INTRODUCTION

The geologic and thermodynamic characteristics of the Salton Sea geothermal system were described in great detail by Helgeson [1968]. He showed plots of depth versus temperature, pore-fluid pressure, and total dissolved solids for many of the wells that had been drilled at that time. A characteristic of the system is that fluids with different salinities are produced from different wells. The data strongly suggested that within the hydrothermal system the salinity increases from the sides toward the central part of the field, and from the top toward the bottom. The thermal gradients in wells in the central part of the field generally are nearly linear from the surface to a depth of about 0.5 to 1 km and range from about 250° to 380°C km⁻¹. Below about 1 km, thermal gradients generally are nearly linear, but at much lower values (commonly about 40°C km⁻¹). The gradient measured within the State 2-14 Salton Sea Scientific Drill Hole (SSSDH) from a depth of 1,890 to 3,170 m is about 39°C km⁻¹ [Sass et al., 1987]. According to Helgeson [1968], pressures measured at perforations in various wells under static conditions fall on a curve with a 0.0295 atmosphere ft⁻¹ gradient--a pressure gradient which requires the brines to have virtually unit specific density at all depths (to at least 7,000 ft, the deepest measurement at that time). Since then there have been no published papers that dispute these observations. Rex [1985] agreed that temperature and salinity achieve a balance with specific density of the fluid equal to unity, and stated that according to his study this phenomenon is an intrinsic property of the reservoir.

The observed thermal profile within the Salton Sea geothermal system is typical of geothermal systems that are capped by impermeable rock through which heat is transferred mainly by conduction, and are underlain by relatively permeable rock through which heat is trans-

ferred mainly by convection. Helgeson [1968] recognized that this interpretation of the data presented a paradox: the high heat flow through the top part of the system and the relatively low thermal gradient below the impermeable cap required convective transfer of thermal energy within the hydrothermal system, while a hydrostatic gradient exactly consistent with unit density and systematically increasing salinity with depth precluded free convection in the geothermal reservoir. In view of this paradox, Helgeson [1968] suggested that below about 0.9 to 1.2 km (3,000-4,000 ft) the salinity of the reservoir fluids in a given well may be constant with increasing depth, and that the uncertainty in the pore-fluid pressure measurements was too great to distinguish between isosalinity and isodensity conditions. Helgeson [1968] did note, however, that the model that he proposed was only one of several possible convective mechanisms of heat transfer that might be operating in the reservoir. As an example of other mechanisms, he called attention to the paper by Turner and Stommel [1964] on double-diffusive convection. It is the intent of this paper to again call attention to double-diffusive convection and to suggest that this process be given more consideration as a possible way to explain the variations in pressure, temperature, heat flow, and salinity observed throughout the hydrothermal system.

PREVIOUS MODELS OF THE HYDROTHERMAL SYSTEM

White [1968] and Dutcher et al. [1972] suggested that vertical heat transport in the Salton Sea field is by large-scale convection cells encompassing the entire section of permeable reservoir rocks. However, this suggestion does not account for the reported variations in composition of the brine from bottom to top and center to sides. In the Helgeson [1968] model localized free convection of the brine is favored--uniform salinity occurring within a given well but different salinities in adjacent wells.

Yonker et al. [1982] suggested that vertical convective motion in the reservoir beneath the thermal cap is confined to small units within permeable sand horizons interbedded with and separated by thin shale beds. They further suggest that large-scale horizontal flow could be superimposed on the small-scale convection to transfer heat from the area of the buttes, which is close to the southern shore of the Salton Sea, to the margins of the field. This lateral-flow model was expanded upon by Kasameyer et al. [1984], who shows the heat source as a region of dike intrusion at the side of the region of horizontal fluid convection.

Rex [1985] concluded that the main reservoir is not undergoing significant convection but

rather owes its condition to a balance of osmotic and thermo-osmotic effects combined with water-rock interactions. He further concluded that the geothermal reservoir does not need a cap rock but is hydrostatically stable, capped by a ground-water circulation system. In this model, diffusion of water downward plays a major role in the development of the salinity gradient, and the decrease in thermal gradient below about 1 km appears to reflect changes in bulk conductivity of the rock-brine system with depth. Michels [1987] also discussed a model in which salinity gradients develop in non-convecting brine in response to a temperature gradient.

DOUBLE-DIFFUSIVE CONVECTION

The processes involved in double-diffusive convection have been described and reviewed by many investigators, including Stommel et al. [1956], Turner and Stommel [1964], Turner [1974, 1979, 1981], Huppert and Turner [1981], Huppert and Sparks [1984], and Vitagliano et al. [1984]. Double-diffusive convection resulting in layered cells has been applied in geologic environments to explain temperature-salinity profiles in some ocean environments [Stommel et al., 1956; Huppert and Turner, 1981] and to account for stratified chemical variations and mineral banding in some magma chambers [Huppert and Turner, 1981; Huppert and Sparks, 1984]. However, Griffiths [1981] suggested that it might occur in geothermal systems. The two requirements for the occurrence of double-diffusive convection are that the fluid contain two or more components with different molecular diffusivities, and that these components make opposing contributions to the vertical density gradient [Huppert and Turner, 1981]. Within the Salton Sea hydrothermal system the important parameters are the contrasting rates of transport of heat and salt across a boundary layer separating cooler less saline water above from hotter more saline water below. Both heat and salt are transported through the interface solely by molecular diffusion. The fluid mechanical behavior for this situation was first studied experimentally by Stommel in 1962 and described by Turner and Stommel in 1964.

Thermal input from below into the deeper more saline water causes it to become less dense than the overlying less saline water and convection is initiated. Upward movement of the more saline water continues until a slight cooling increases its density to the point where buoyancy is no longer a driving force. Huppert and Turner [1981] describe the process as follows: "After the initial oscillatory instability, the thermal boundary layer breaks down to form a shallow convecting layer that grows by incorporating fluid from the gradient region above it. When the thermal boundary layer ahead of the convecting region reaches

a critical Rayleigh number, it too becomes unstable, and a second layer forms above the first. Convection is sustained by a more rapid vertical transport of heat relative to salt, and eventually many such layers form." For the situation in which there are horizontal as well as vertical temperature and salinity gradients, individual double-diffusive convection cells should be bounded on the sides by other convection cells that have slightly different salinities and temperatures.

Within the Salton Sea hydrothermal system, the situation is greatly complicated by the heat stored in the surrounding rock and by convective flow of fluids, mainly within relatively permeable sands toward the top of the system, and mainly within interconnecting fractures where rock has been indurated by metamorphic processes. However, Griffiths [1981] has demonstrated experimentally that layered double-diffusive convection cells can form in porous media, and has suggested that some chemical variations at Wairakei may be due to this effect. If double-diffusive convection does occur in porous media or in open fractures within the Salton Sea geothermal system, it is likely that the temperatures of the wall rocks would adjust to the temperatures of the many-layered convection cells. Thus, on a gross scale the thermal gradient might be relatively uniform at about $40^{\circ}\text{C km}^{-1}$, but on a fine scale the thermal profile would have a staircase structure (Figure 1). Future temperature logging, after the SSSDH has had casing cemented in place to near the bottom and after the well has returned to thermal equilibrium, may provide critical information with which to evaluate the possibility of double-diffusive convection within the system.

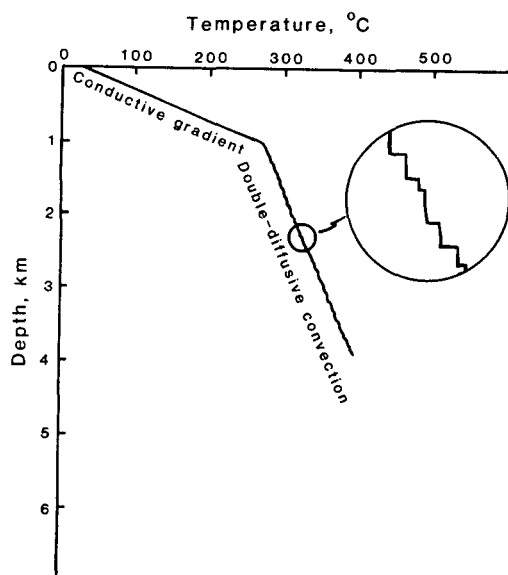


Figure 1. Idealized temperature-depth profile within the Salton Sea geothermal system showing details of effects of double-diffusive convection.

THE FLUID COMPOSITION-DENSITY PROFILE

It is essential that reliable and accurate fluid composition and density profiles be established for the Salton Sea hydrothermal system at several localities in order to choose among possible hydrologic models of the system. Rex [1985] implies that the available data (apparently mostly residing in company files) are sufficient to do this. The basic data, however, have not been published for scrutiny by the scientific community. Much of the available information is difficult to evaluate, because commercial production wells generally are completed with long sections of slotted liners so that fluids sampled at the wellhead may be mixtures of brines from different depths where slightly different initial temperatures prevail.

If it can be shown that salinities really do systematically increase with depth and that fluid densities really do remain close to unity at all depths within the hydrothermal system, free convection would be eliminated as a mechanism of heat transfer, and double-diffusive convection would become a more attractive, though not the only, model to account for the thermal and chemical structure of that system. A major objective of the SSSDH was to address this problem by sampling and analyzing uncontaminated fluid samples from isolated regions at different depths in the well. To date, an uncontaminated fluid sample has been obtained from that well only from a depth interval of 1,865 to 1,877 m and an initial temperature of 305°C [Michels, 1986; Sass et al., 1987; Thompson and Fournier, in press]. The calculated pre-flashed composition of that fluid is shown in Table 1. Although the results provide information about only one point on the depth-composition curve, that point is well constrained, and it can be used as a basis for estimating what the properties of pore fluids should be at shallower and deeper levels in the well.

Table 1. Pre-flashed concentrations of selected elements and total dissolved solids in brine from a depth of 1,865-1,877 m in the State 2-14 well, December 1985 flow test.

Weight %	12/29*	12/29**	12/30**
Na	5.01	5.28	5.27
K	1.72	1.67	1.65
Ca	3.32	2.71	2.65
Cl	15.15	15.34	15.37
Sum	25.20	25.00	24.94
Total dissolved solids	25.2-25.7	25.54	25.46

* Thompson and Fournier [in press]

** Michels [1986]

During drilling, the mud weight required to just balance the pore-fluid pressure at a depth of 1,879 m indicated a pore-fluid density very close to 1 g cm^{-3} (Sass, pers. commun., 1986). No down-hole pressure measurements were made at that depth, and down-hole fluid sampling was unsuccessful. Consequently, the only available check on the pore-fluid density is by calculation, using the pre-flashed composition of the brine sampled at the surface (Table 1). The fluid produced from a depth of about 1,870 m is composed predominantly of NaCl, CaCl_2 , and KCl, and the total dissolved solids are about 25.5 ± 0.3 weight percent. For this type of brine, the density at high temperature and high pressure can be calculated by using a model published by Potter and Haas [1978]. In that model the density of the brine, d_b , is related to the composition of the brine as follows:

$$d_b = d_N + (d_K - d_N)f_K + (d_C - d_N)f_C, \quad (1)$$

where d_N , d_K , and d_C are the densities of pure solutions of NaCl, KCl, and CaCl_2 , respectively, at the given temperature and molality of the total chloride in solution; and f_K and f_C are the mole fractions of chloride present in the brine as KCl and CaCl_2 , respectively.

Densities of the pure chloride solutions of the three salts were taken from Potter and Brown [1976, 1977] and Potter and Clyne [1976]. Density data for KCl at temperatures in the 200° to 400°C range extend only to about 4-m solutions, so densities of a more concentrated solution ranging from 4.0 to 5.8 m were obtained by extrapolation, using a plot of molality chloride versus the difference in density of KCl and NaCl for solutions of the same molality in respect to chloride. That plot and a similar plot with CaCl_2 instead of KCl give straight lines (Figure 2). Density data for both KCl and CaCl_2 are available only at the vapor pressures of the solutions, and density data for CaCl_2 are not available above 300°C . Therefore, densities of the predominantly NaCl- CaCl_2 -KCl pre-flashed reservoir fluid [Michels, 1986; Thompson and Fournier, in press] were calculated at 300°C and the vapor pressure of the solution, and then those results were multiplied by factors to correct for the slightly increased temperature and pressure actually present in the reservoir. The correction factors were obtained by assuming that the changes in density caused by increased temperature and pressure were proportional to the changes in density caused by similar increases in temperature and pressure in the pure NaCl system. The temperature-correction factor that was used required multiplication of the density (calculated at 300°C) and the vapor pressure of the solution by 0.995. The pressure-correction factor required multiplication by 1.019. These corrections for temperature and pressure act in opposite directions, and the combined correction factor requires multiplication by 1.014. The exclusion of iron and

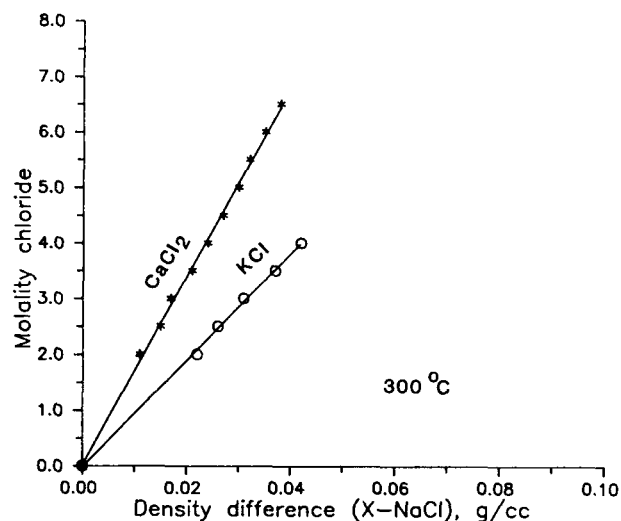


Figure 2. Chloride molality versus the density difference between the indicated salt and NaCl at 300°C . The symbols show data obtained from tables of densities.

other dissolved constituents from the density model is not likely to have made a significant difference, even though they constitute about 2 weight percent of the total dissolved solids, because the model is based mainly on the total chloride in the system. In the Thompson and Fournier data shown in Table 1, all the anionic charges were assumed to be balanced by sodium, calcium, and potassium, thereby compensating in great part for the absence of other dissolved constituents in the density calculation [Thompson and Fournier, in press].

Calculated densities of pre-flashed reservoir fluids produced from the SSSDH at a depth of 1,865 to 1,877 m and a temperature of 305°C are shown in Table 2. The three different sets of analytical information yield a calculated average density of 1.0008 ± 0.0023 . This result is in agreement with a double-diffusive model in which hot brines are in approximate pressure equilibrium with cold water at the sides of the hydrothermal system. The errors caused by not taking account of small amounts of other constituents in the brines, such as iron and manganese, and assuming a model based on pure NaCl to correct for pressures greater than the vapor pressure of the solution and a temperature of 305°C instead of 300°C , will cause the calculated density to be slightly on the low side. Therefore, the chemical data favor reservoir fluid densities of about 1 g cm^{-3} or greater at a depth of 1,870 m. The free convection model of Helgeson [1968] requires a fluid density of less than 1 g cm^{-3} (about 0.97 – 0.98 g cm^{-3}) at a depth of 1.8 km. Conversely, for isochemical conditions in a freely convecting system, brine of the composition found at 1.8 km would have a density of about 1.02 to 1.03 g cm^{-3} at a depth of 1 km and a temperature of 275°C . That high a fluid density

TABLE 2. Calculation of specific density of pre-flashed brine at 305°C at a depth of 1,865-1,877 m in the State 2-14 well. (The notation is given in the text.)

	Dec. 29*	Dec. 29**	Dec. 30**
$d_K - d_N$	0.0604	0.0603	0.0602
$d_C - d_N$	0.0336	0.335	0.335
f_K	0.1029	0.0987	0.0973
f_C	0.3877	0.3125	0.3050
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d_{Na}	0.9702	0.9698	0.9696
$(d_K - d_N) f_K$	0.0062	0.0058	0.0059
$(d_C - d_N) f_C$	0.0130	0.0105	0.0102
Sum	0.9894	0.9862	0.9857
P-T correction	x 1.0139	x 1.0139	x 1.0139
	=====	=====	=====
Density at 305°C	1.0031	0.9999	0.9994

* Thompson and Fournier [in press]

** Michels [1986]

in the shallow part of the system is not consistent with the observed pressures or with free convection driven by the influx of cold dilute water at the sides of the system.

DISCUSSION AND CONCLUSIONS

The suggestion made by Helgeson [1986] that the salinity of the reservoir fluid in a given well may be constant with increasing depth below about 0.9 to 1.2 km still seems to be a possibility, although a remote one. The critical experiment, in which fluids would be sampled and analyzed from significantly different depths within a given well, has not yet been carried out. Another flow test of the SSSDH from an isolated zone at a depth of about 3,000 m could provide critical information with regard to the possibility of free convection occurring in the 1,800 to 3,000 m depth range.

The models proposed by Rex [1985] and Michels [1987] assume that salinity increases with depth and that little convective flow occurs. However, Rex [1985] would have very slow horizontal flow of the brine southward from the Salton Sink as far as the town of Imperial, a distance of approximately 50 km. Neither Rex [1985] nor Michels [1987] addresses the problem of how to supply large quantities of heat from the base of the system to the top without a significant component of convective heat transport. Rex [1985] simply states that the observed decrease in temperature gradient with depth does not indicate convection in the reservoir, but rather a change in bulk conductivity of the rock-brine system with depth.

The model proposed by Yonker et al. [1982] and Kasameyer et al. [1984] can account for the thermal structure and lack of large-scale vertical convection that would homogenize fluids in the upper part of the hydrothermal system where permeability is controlled by horizontally bedded alternating sands and shales. However, the model does not address the apparent lack of vertical convection in the deeper parts of the system, where fluids may flow through fractures in highly altered and indurated rocks. This model seems to require stagnant conditions where fracture permeability predominates, but could be compatible with slow free convection of an isochemical fluid or double-diffusive convection of fluids with increasing salinity at depth. In addition, this model does not address recharge of highly saline brines of different compositions into the different permeable sandstones in the upper part of the hydrothermal system, where horizontal flow is occurring beneath the thermal cap; nor does it explain why temperature-salinity relations in the pore waters appear to adjust to a specific density of unity in each of the cells. The model also seems to imply that salinities should remain constant within any given sand horizon from the center of the system to near the margin, where mixing with cold dilute water occurs.

The calculated density of the brine sampled from the SSSDH at a depth of 1,865 to 1,877 m is close to unity at 305°C and 18.7 MPa. This result is in agreement with a hydrologic model in which hot brines are in hydrostatic equilibrium with cold dilute water surrounding the hydrothermal system. It also is in agreement with a model in which salinity gradients and heat flux are controlled by double-diffusive convection within the hydrothermal system. A depth-temperature-salinity profile in which specific densities of fluids are everywhere close to unity does not in itself prove that double-diffusive convection is occurring. However, double-diffusive convection has been demonstrated experimentally in porous media [Griffiths, 1981], and it should be given additional consideration as a mechanism for explaining the vertical and horizontal chemical gradients and the high heat flux from the Salton Sea geothermal system. It may offer a plausible alternative or an important adjunct to the models of Yonker et al. [1982] and Kasameyer et al. [1984].

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