DOUBLE-DIFFUSIVE CONVECTIVE TRANSFER OF THERMAL ENERGY WITHIN THE SALTON SEA GEOTHERMAL BRINE

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INTRODUCTION

Helgeson (1968) noted the following characteristics of the Salton Sea geothermal system: (1) the salinity of the brine in the geothermal reservoir increases from the top toward the bottom and from the sides toward the center, (2) fluid densities, determined from pressure measurements at perforations in cased wells, are about equal to 1 g cm^{-2} at all depths of production, (3) 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}, and (4) below about 1 km thermal gradients also are nearly linear, but commonly are about 40°C km^{-1}. Since 1968 there have been no published reports that dispute these observations. Rex (1985) agreed that temperature and salinity achieve a balance with density of the fluid equal to 1 g cm^{-2}, and stated that according to his study this phenomenon is an intrinsic property of the reservoir.

The observed thermal profiles within the Salton Sea geothermal system are typical of geothermal systems that are capped by impermeable rock through which heat is transferred mainly by conduction, and that are underlain by relatively permeable rock through which heat is transferred largely by convective upflow. Helgeson (1968) recognized that this interpretation of the data presented a paradox: a high heat flow through the top part of the system and a relatively low thermal gradient below the impermeable cap require convective transfer of thermal energy within the hydrothermal system, while a hydrostatic gradient exactly consistent with unit density and systematically increasing salinity with depth preclude free convection in the geothermal reservoir. In view of this paradox, he suggested that below about 0.9 to 1.2 km the salinity of the reservoir fluid in a given well may be constant with increasing depth (but different from well to well), 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.

OTHER THERMAL AND CHEMICAL MODELS OF THE SALTON SEA 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.

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 suggested 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 show the heat source as a region of dike intrusion at the side of the region of horizontal fluid convection.

The Yonker et al. (1982) and Kasameyer et al. (1984) model can account for the thermal structure and lack of large-scale vertical convection that would homogenize fluids in the upper part of a 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 across bedding units through fractures in highly altered and indurated rocks. The model seems to require stagnant conditions where fracture permeability predominates. 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 assumed to occur 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.

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. Michels (1987) also discussed a model in which salinity gradients develop in nonconvecting brine in response to a temperature gradient. Neither Rex (1985) nor Michels (1987) adequately address 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 thermal conductivity of the rock-brine system with depth.

DOUBLE-DIFFUSIVE CONVECTION

The processes involved in double-diffusive convection have been described and reviewed by many investigators, especially Huppert and Turner (1981). 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. 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 (1962) and described by Turner and Stommel (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.

Double-diffusive convection has been employed as a mechanism to explain temperature and composition profiles in several types of natural all-liquid systems, such as ocean water overlain by fresher water (Stommel et al., 1956; Huppert and Turner, 1981), and melts in magma chambers (Huppert and Turner, 1981; Huppert and Sparks, 1984). Within the Salton Sea hydrothermal system, the situation is greatly complicated by the heat stored in the surrounding rock and by convective flow of liquids through permeable rock; mainly within relatively permeable sands toward the top of the system, and mainly within interconnecting fractures deep in the system where all rock types have been altered and 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 so that on a gross scale the thermal gradient might be relatively uniform at about 40°C km^{-1}, but on a fine scale the thermal profile would have a staircase structure (Figure 1).

It is essential that accurate fluid composition and density profiles be established for the Salton Sea hydrothermal system at several localities in order to further develop and test hydrologic models of the system. 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 different initial temperatures prevail. A major objective of a recently completed Salton Sea Scientific Drill Hole (SSSDH) was to sample and analyze uncontaminated fluid samples from isolated regions at different depths in the well. However, uncontaminated fluid was obtained 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). Calculated preflashed compositions and densities of three samples of that fluid are shown in Table 1. Densities were calculated using a model published by Potter and Haas (1978). The different sets of analyses yield a calculated average density of 1.0008 ± 0.0023. Although the results provide information about only one point on the depth-composition curve, that point is well constrained, and it is in complete agreement with a double-diffusive model.

The free convection model of Helgeson (1968) requires a fluid density of about 0.97 to 0.98 g cm^{-3} at a depth of 1.8 km, which is significantly lower than the density calculated using the collected fluid samples. Conversely, for isochemical conditions, at a depth of 1 km and a temperature of 275°C, brine of the composition found at 1.8 km in the SSSDH would have a

Table 1. Pre-flashed concentrations of selected elements, total dissolved solids, and calculated specific densities of brine samples from a depth of 1,865 to 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
Calculated density at 305°C	1.0031	0.9999	0.9994

* Thompson and Fournier [in press]
** Michels [1986]

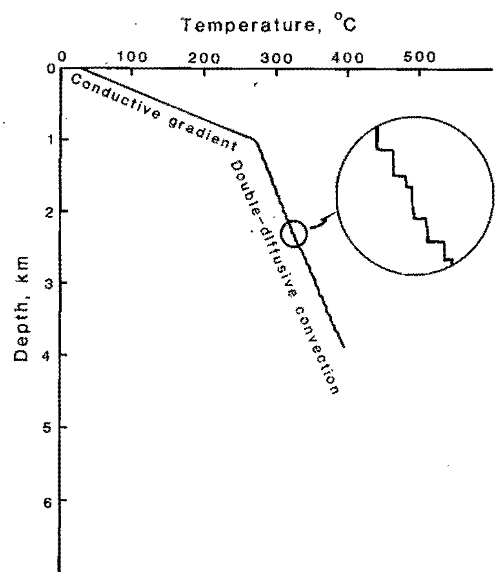

Figure 1. Idealized temperature-depth profile within the Salton Sea geothermal system showing details of effects of double-diffusive convection.

density of about 1.02 to 1.03 g cm^{-3}. That high a fluid density in the shallow part of the system is not consistent with the observed pressures or with thermally driven free convection. Double-diffusuve convection is consistent with all of the reported physical and chemical characteristics of the Salton Sea brine. It provides a mechanism for the convective transfer of heat from the bottom to the top of the system while maintaining chemical gradients.

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