BRINE CIRCULATION AND HOT-PLATE FORMATION

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ABSTRACT - A modified version of the numerical reservoir simulator MULKOM, using prototype subroutines modelling the state-space and physical and thermodynamic properties of the two component system H_2O-NaCl over a wide range of temperatures and pressures [$0 < T < 1075$ °C, $0 < p < 1600$ bars abs], was tested on a model of thermal convection over a mid-ocean ridge magmatic hot-plate.

1. INTRODUCTION

Chloride waters are known to be a common characteristic of liquid dominated geothermal fields (Ellis & Wilson, 1955), to play a dominant role in the formation of porphyry copper (Henley & McNabb, 1978) and other ore deposits, and to possess dense fluid phases at high temperatures and pressures with the potential to control the fluid output temperatures of "black smokers" (McNabb & Fenner, 1985) and other geothermal plumes (McNabb, 1992).

A numerical simulator able to handle high pressure and temperature brines of all concentrations could be a valuable tool for a better understanding of all of these processes, as well as a first step towards more realistically modelling many other ore transport and deposition phenomena. The two component system H_2O-NaCl has a very high temperature and pressure critical point so that such fluids undergo phase transitions in high pressure environments near magmatic temperatures. Such phase changes can result in dramatic concentration changes in other minor chemical contaminants of the fluids and result in their precipitation in the right environment. Moreover, the dense hot brines can have densities exceeding that of cold water so that they can form stably-stratified layers at depth which effectively shield the ground-water from the highest magmatic temperatures.

It is a common experience when modelling fluid flow in meteorology, geothermal fields and industrial processes to find that phase changes play a dominant role in the global behaviour of the system, supposedly because they produce sudden changes in the physical properties of the fluid, thereby creating buoyancy effects due to density changes, releases of thermal energy due to latent heat effects and dramatic changes in chemical concentrations. Such phase changes are at the heart of the "engine" driving tropical cyclones, and provide an explanation for the strange "candle-flame structure" of copper ore deposits as well as for the surprisingly low temperatures of geothermal plumes supposedly heated by molten magma at depth. They also make the systems mathematically complex and difficult to model analytically and, needless to say, numerically.

This paper is part of a project to test the feasibility of modifying the numerical reservoir simulator MULKOM (Pruess, 1983) to handle these multi-component multi-phase fluids and is motivated by the vision of a multi-component program incorporating all the phase properties of the H_2O-NaCl-CO_2 system carrying various ores and minerals such as lead, zinc, copper, gold and scheelite, and with the potential to predict deposition environments that can be matched with fluid inclusion data to guide exploration endeavours.

A first step towards modelling these multi-component fluids involves the delineation of their thermodynamic and relevant physical properties beginning with a phase-space map of all the various co-existing solid, liquid and vapour phases, the compositions of co-existing phases and assembling of subroutines to generate their densities, enthalpies and viscosities.

Such subroutines for the two-component system H_2O-NaCl are discussed in another paper presented at this Workshop (McKibbin & McNabb, 1993) and we have chosen, as a viability test, to use our modified version of the numerical reservoir simulator MULKOM, incorporating these subroutines, to model thermal convection of sea water at depths typically found at mid-ocean ridges.

2. SUB-SEAFLOOR HYDROTHERMAL SYSTEMS

Submarine exploration of sea-floor spreading zones led to the discovery of hydrothermal activity and unexpectedly high temperature water (near 400 °C) issuing from vents on the sea-floor (Speiss *et al.*, 1980).

Bischoff (1980) concluded from a study of data relating to such fluid discharges at 21°N on the East Pacific Rise that the maximum subsurface fluid temperature was about 420 °C.

McNabb and Fenner (1985) raised the question, "if the heat source driving the convection is magma at temperatures near 1200 °C, why do we not find hotter subsurface fluid temperatures?" They suggested the existence of a stably-stratified layer of dense hot brine fluid shielding the convecting sea-water from the magmatic temperatures.

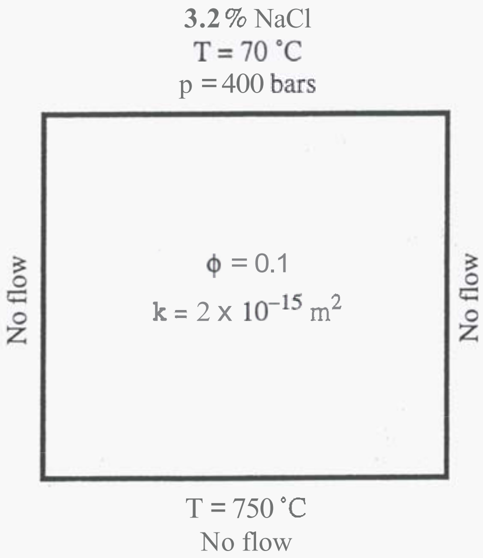

Figure 1. Schematic cross-section of the reservoir used for the model problem, with all sides of length 1 km, and with matrix properties and boundary conditions as marked.

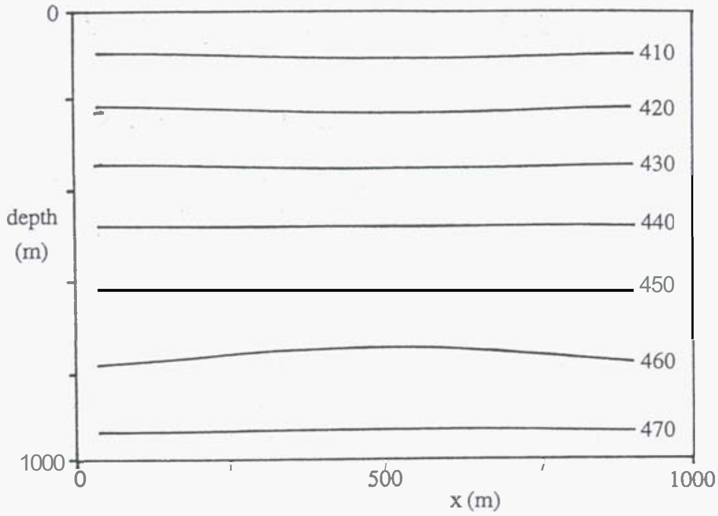

Figure 2. Pressure contours at steady-state flow for the model problem. Isobaric values are marked in bars absolute.

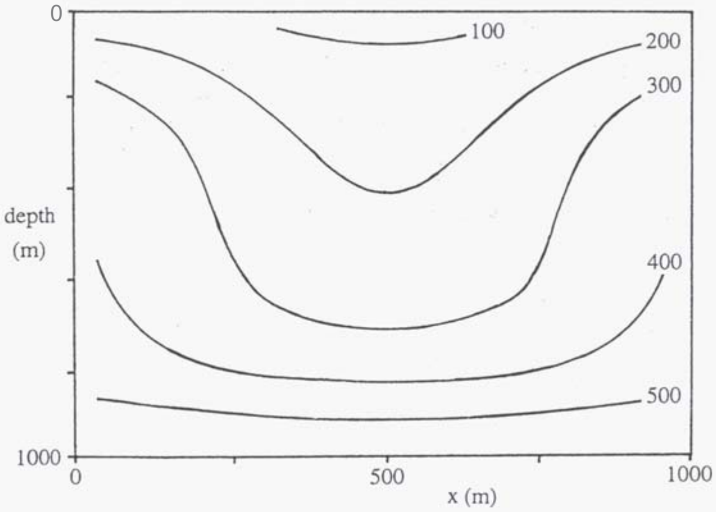

Figure 3. Temperature contours at steady-state flow for the model problem. Isothermal values are marked in "C.

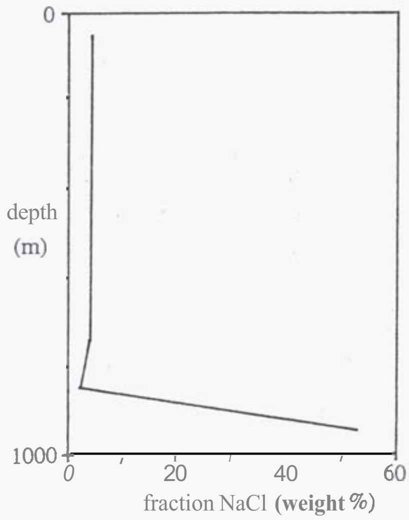

Figure **4.** Profile with depth of salinity in weight % at the central line of downflow (x = 500 m) of the model problem.

At the pressures prevailing on the mid-ocean ridge sea-floor (300-500 bars) a potential control mechanism could operate to preserve a stratified dense brine "hot-plate" for sea-water convection with a top surface temperature of about 450 "C. At higher temperatures, sea-water forms a second dense brine phase which is left behind and thickens the heat conducting dense brine layer eventually leading to lower top surface temperatures. At lower "hot-plate" temperatures, salt is dissolved from the dense brine layer making it thinner and so more conducting. The net result is that the mean salt concentration in the hydrothermal fluid is that of sea-water, and the brine "hot-plate" temperature is about 450 "C.

This concept of dense brines over the magma and near sea-water salt concentrations is compatible with the findings of Nehlig (1991) who recorded salinities in fluid inclusions from Semail and Trinity ophiolites varying between 0.3 and 52 wt% NaCl. Whereas most samples had only slightly higher salt concentrations than sea-water, some exhibited very high salinities. These high values were restricted to the plagiogranites which mark the top of the fossil magma chamber.

The same concept of a dense brine "hot-plate" as a temperature control mechanism for hydrothermal plumes was developed by McNabb (1992) for geothermal plumes in ground water for cases where there is a magmatic chloride input from below.

3. HYDROTHERMAL MODEL

Our test program assumed a two-dimensional square reservoir (see Figure 1) with sides of length one kilometre, of a homogeneous porous medium with porosity $\phi = 0.1$ and permeability $k = 2 \times 10^{-15}$ m^2, with an open top and with impermeable sides and bottom. The top surface was open to the sea at a pressure of 400 bars, and the bottom was assumed to be at a temperature of 750 'C.

This low Rayleigh number flow stabilised to a steady convective regime with pressure and temperature as shown in Figures 2 and 3. The profile with depth of salinity (in weight %) at the central line of downflow ($x = 500$) is shown in Figure 4.

The interesting feature of these distributions is the concentration of the high-salinity contours over the "hot-plate", confirming the concepts described earlier and the viability of the thermal control mechanism.

4. CONCLUSIONS

Our modifications of MULKOM accommodate the properties of brines; they work, and the program generates believable solutions over the pressure and temperature ranges of current interest. We are happy with the important features concerning phase properties and fluid densities but feel we must wait for better data to adequately describe the fluid enthalpies and viscosities over the full range of our thermodynamic variables.

The program suffered from some convergence difficulties requiring small time steps in the high-temperature two-fluid regime, switching from one fluid to the other during iterations. There is probably a technical solution to this problem.

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