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VAPOR-DOMINATED ZONES WITHIN HYDROTHERMAL CONVECTION SYSTEMS

S. E. Ingebritsen

U. S. Geological Survey, Menlo Park, CA 94025

ABSTRACT

Three conceptual models are presented to illustrate the range of natural hydrothermal convection systems in which vapor-dominated conditions are found. Numerical simulation is used to test the feasibility of these models and to demonstrate geologically plausible evolutionary pathways for each model.

INTRODUCTION

How vapor-dominated zones evolve and how they behave in the natural state is not well understood, partly because of their scarcity and partly because of the difficulty of quantitatively describing two-phase systems. The goal of this study was to simulate the behavior of three model systems that represent the range of hydrothermal convection systems within which vapor-dominated conditions are found (fig. 1) and to quantitatively investigate the conditions that allow each system to evolve.

For the purposes of this study, vapor-dominated zones are considered to be those in which the mass flux of vapor is somewhat greater than the liquid flux ($|q_s/q_w| > 1$) and relative permeability to steam is much greater than relative permeability to water ($k_{rs}/k_{rw} >> 1$). A criterion based only on the vertical pressure gradient would not include the third conceptual model (fig. 1).

The conceptual models range from a system with an extensive vapor-dominated zone that is generally underpressured with respect to the local hydrostatic pressure (fig. 1 - Model I) to a system that includes a relatively thin vapor-dominated zone at pressures above local hydrostatic (fig. 1 - Model III). Although each model has unique features, they have some characteristics in common. They each involve phase separation at pressures significantly greater than atmospheric and include zones in which vapor is by far the more mobile phase (relative to liquid water). Each is associated with fumaroles and steam-heated low-chloride acid-sulfate springs, as a result of the phase separation. The vapor-dominated zones in Models II and III are both "parasitic" to relatively voluminous throughflows of liquid that also feed high-chloride thermal springs at lower elevations.

Most natural systems are significantly more complex than the models shown in figure 1, and some might be better represented as a combination of the models. Active systems such as The Geysers, Larderello (Italy), Kamojang (Indonesia), and Matsukawa (Japan) are generally similar to Model I. A relatively large number of high-temperature systems in regions of topographic relief are similar to either Model II or Model III (Ingebritsen, 1986); however, in most cases the thickness and pressure distribution within the vapor-dominated zone are unknown. Sumikawa, Japan (Y. Kubota, written commun., 1986) may be similar to Model II. Mud Volcanoes, Yellowstone and Rotorua, New Zealand (B. Simpson, oral commun., 1986) may be similar to Model III.

NUMERICAL SIMULATION

The conceptual models shown in figure 1 were simulated using a modified version of the GEOTHER code described by Faust and Mercer (1979a, 1979b; Mercer and Faust, 1979). This code simulates three-dimensional single- and two-phase heat and mass transport in a porous medium. Modifications to the original GEOTHER code and the limitations of the code with respect to the natural systems modeled are described by Ingebritsen (1986).

MODEL I

Within the extensive vapor-dominated zone in Model I (fig. 1; White and others, 1971) the vertical

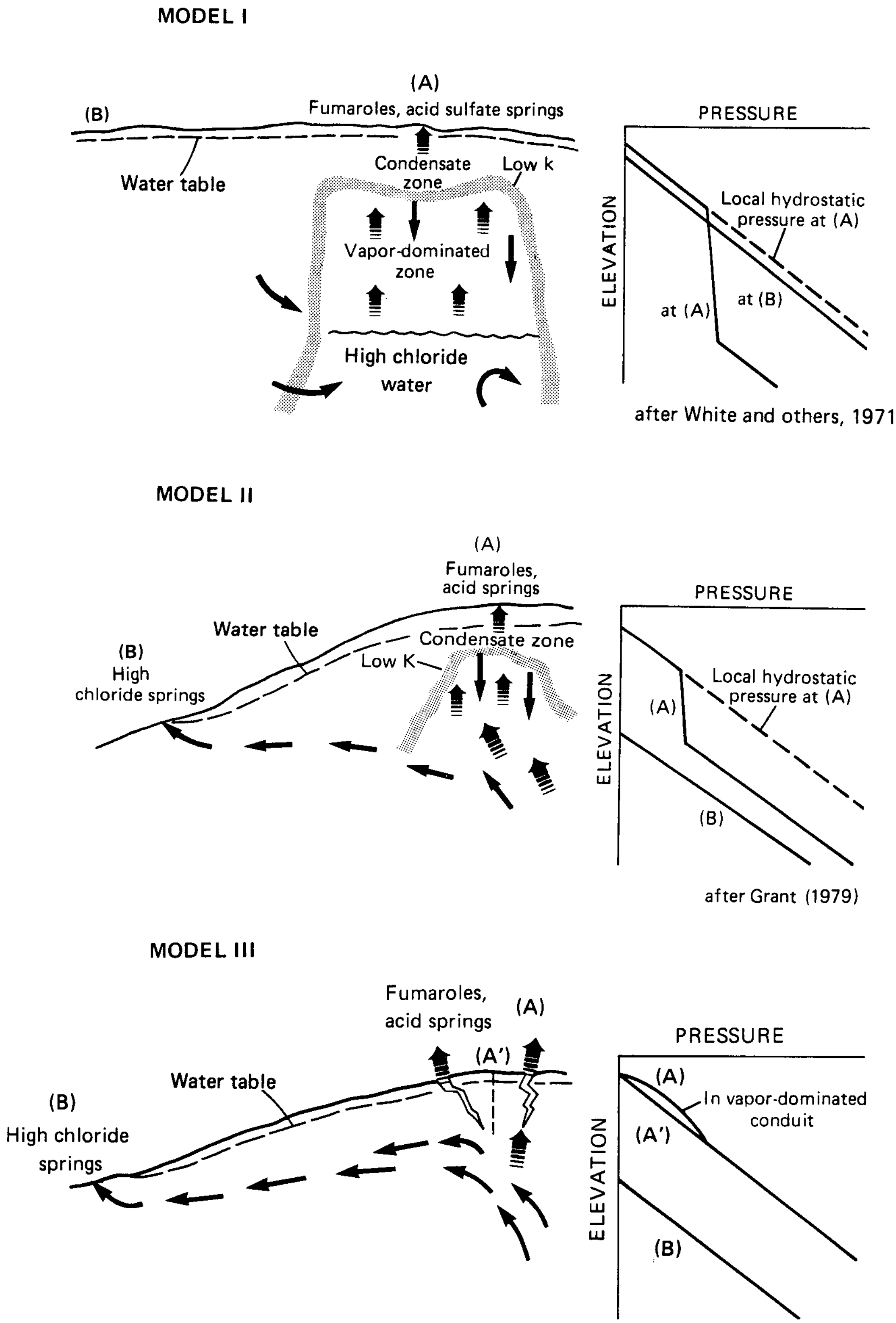

Figure 1. Conceptual models of three hydrothermal convection systems that include vapor-dominated zones. Broken arrows represent steam, solid arrows liquid water.

pressure gradient is somewhat above vaporstatic. There is steam/liquid counterflow within the vapor-dominated zone, as a fraction of the rising steam condenses and flows back down in narrower channels and pore spaces. The vapor-dominated zone is generally underpressured with respect to local hydrostatic pressures (fig. 1), so, to exist, it must be isolated from surrounding nonthermal flow systems by low-permeability barriers.

The vapor-dominated zone is overlain by a condensate zone that is liquid saturated, or nearly so (fig. 1). The vapor-dominated zone is presumably underlain by a zone of high-chloride liquid, but there is no evidence for voluminous liquid throughflow.

Geometric model

Model I is represented geometrically as a two-dimensional vertical cross section, with no boundaries closed to mass or energy (fig. 2a). The land surface is treated as a uniform constant pressure/enthalpy boundary, at a pressure of 1 bar and an enthalpy equivalent to 15°C. The system is flanked by nonthermal flow systems - also represented by constant pressure/enthalpy boundaries - but buffered to some extent by low-permeability barriers (k_l). The lower boundary is a controlled flux boundary. Some of the numerical simulations involved only conductive heat flux (q_h) at this boundary, and some involved a mass inflow (M) as well as conduction.

This geometric model represents the vapor-dominated zone as an open system. Previous quantitative analyses of such large-scale vapor-dominated zones have involved models with closed boundaries (Pruess and Truesdell, 1980; Pruess and others, 1983; Pruess, 1985) and/or dealt with less global representations of the system (Schubert and Straus, 1979, 1980; Straus and Schubert, 1981; Pruess, 1985).

The series of numerical experiments carried out for Model I involved variations in the lower boundary condition, the geometry of the low-permeability aureole (k_l), and the permeabilities k_h and k_l (fig. 2a). Initial conditions for all of the simulations were a hydrostatic pressure distribution and a low-temperature conductive temperature regime (the same conditions that were maintained at the lateral boundaries throughout the simulations). Total simulation times ranged from 10,000 to 40,000 years.

Results

A vapor-dominated zone such as the one in Model I can evolve within low-permeability barriers without changes in boundary conditions or rock properties, given an adequate supply of heat. The evolution of the system is more rapid in "decreasing recharge" cases that involve a relatively high initial fluid throughflow rate that diminishes through time. White and others (1971) suggested that a likely mechanism for decreasing recharge at depth is loss of permeability due to deposition of carbonates and/or $CaSO_4$, which decrease in solubility with temperature.

The factors most critical to the evolution of systems like Model I are (1) an intense heat source and (2) low-permeability barriers ($\lesssim 10^{-12}$ cm^2) capable of buffering a vapor-dominated zone both vertically and laterally. Since liquid throughflow is limited, the magnitude of the required heat input implies magmatic temperatures within a few kilometers below the vapor-dominated zone.

Given an adequate supply of heat and the appropriate permeability structure, a vapor-dominated zone will begin to develop immediately below a caprock and thicken downward. A permeability contrast at the top of the vapor-dominated zone is critical, because permeability within the vapor-dominated zone must be relatively high ($\gtrsim 10^{-11}$ cm^2). The vapor-dominated zone will continue to thicken as long as the mass of steam leaving the vapor-dominated zone exceeds the mass of liquid inflow. The equilibrium thickness of the vapor-dominated zone is affected by the heat input rate and the permeability of the low-permeability barriers that isolate the vapor-dominated zone laterally. Other factors being equal, a higher heat input rate and less permeable lateral barriers will lead to a thicker vapor-dominated zone. Within the simple geometric model used, vapor-dominated zone pressures vary regularly with depth to the caprock, and are also affected by the geometry of the low-permeability aureole. They are not limited by the pressure of maximum enthalpy of saturated steam (~30.6 bars).

MODELS II AND III

Models II and III (fig. 1) both represent systems that have fumaroles and steam-heated discharge at relatively high elevations and high-chloride springs at relatively low elevations. However, there are basic differences in terms of the nature and

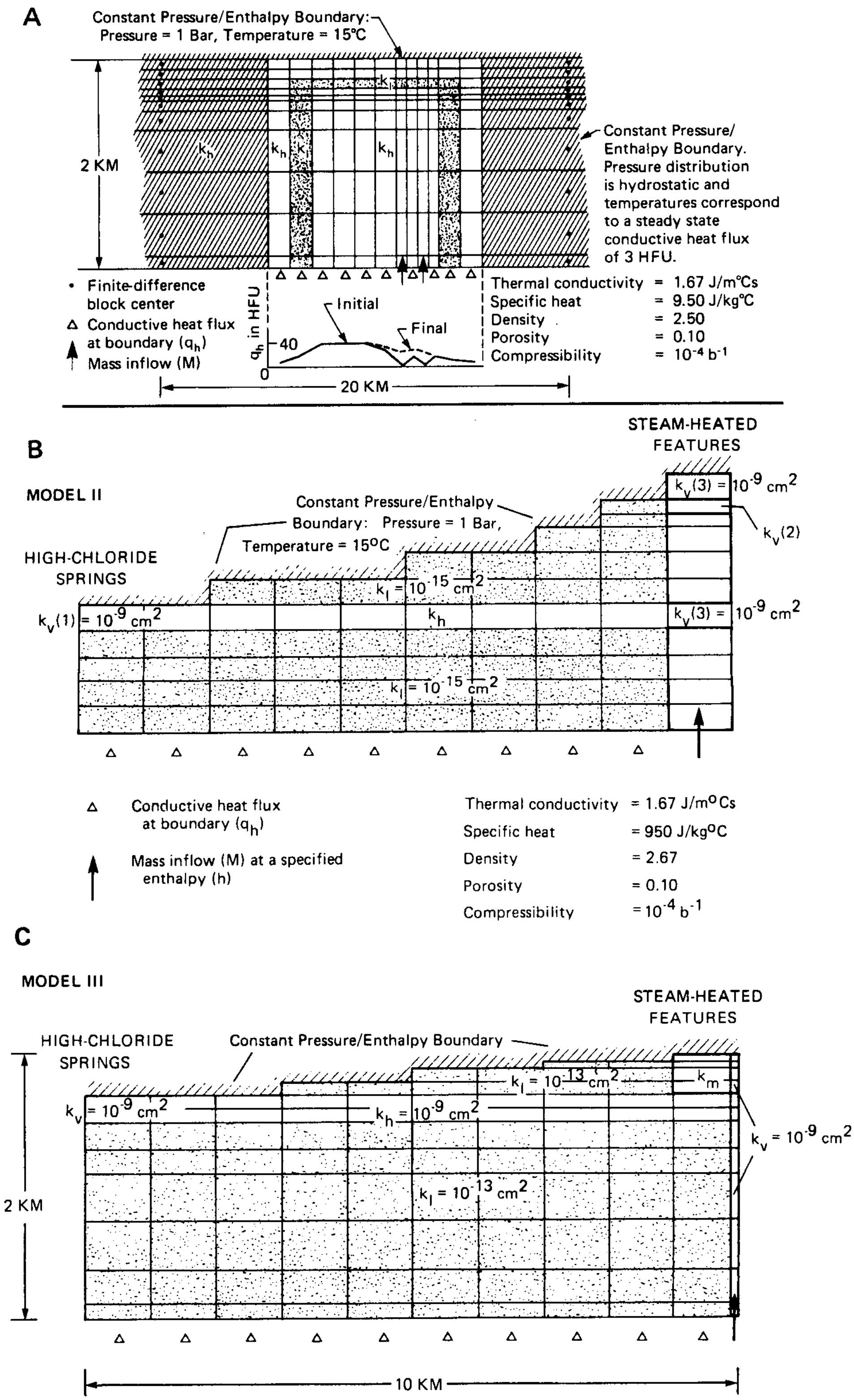

Figure 2 (a) Geometric model used in numerical simulations of Model I.
(b) Geometric models used in numerical simulations of Models II and III.

extent of vapor-dominated conditions.

These systems are distinct from Model I in that the vapor-dominated zones are relatively small and there is a significant throughflow of high-chloride liquid. The elevation difference between the steam-heated features and the high-chloride springs is essential to drive the systems, whereas in Model 1 fluid circulation is controlled largely by density differences.

In Model II, like Model I, phase separation occurs at pressures well below local hydrostatic, the pressure gradient within the vapor-dominated zone is near-vaporstatic, and a low-permeability aureole is required to buffer the vapor-dominated zone from surrounding nonthermal groundwater systems (fig. 1). In Model III, phase separation takes place at pressures close to local hydrostatic pressure (fig. 1), so the overall pressure gradient within the vapor-dominated conduit must be near-hydrostatic. It tends to be somewhat less than hydrostatic immediately above the area of phase separation and above hydrostatic near the land surface, due to expansion of the rising steam (fig. 1). Pressures in the vapor-dominated conduits are somewhat greater than pressures in the surrounding liquid saturated medium, so that low-permeability barriers are not necessarily required. Relative to Model II, high-chloride water is close to the land surface beneath the steam-heated features.

Geometric models

The geometric models shown in figure 2b and 2c were used to represent Models II and III. Both geometric models are two-dimensional vertical cross-sections with sloping upper boundaries. The land surface is treated as a constant pressure/enthalpy boundary and the lower boundary is a controlled flux boundary. Permeability in the patterned regions (k_l) is low enough that fluid circulation within the models is essentially confined to the vertical conduits along the sides (k_v, and k_v and k_m in Model III) and to the lateral conduit (k_h). Fluid circulation is driven by a mass inflow (M) at the lower right, and discharge occurs at the upper right and left sides of the models. A conductive heat flux of 2 HFU is specified along the base of the models, except in the upflow zone.

The values of permeability and other rock properties shown in figures 2b and 2c were used in all of the simulations, and were held constant throughout each simulation. Numerical experiments carried out within these geometric models involved variations in the mass inflow rate M, in the enthalpy of the mass inflow, in k_h and $k_v(2)$ (Model II), and in k_m (Model III). The width of the vertical conduit on the right hand side was also varied in Model III. Initial conditions for all of the simulations were a hydrostatic pressure distribution and a low-temperature conductive temperature regime corresponding to a uniform heat flow of 2 HFU. The simulations were continued until pressures and temperatures in the vertical and lateral conduits became relatively stable (temperatures changing less than 1^oC per 1,000 years). In general, the simulations required 10,000 to 20,000 years to reach this "quasi-steady-state" condition.

Results

Several conditions are necessary for the evolution of the vapor-dominated zone in Model II, including (1) topographic relief; (2) a period of convective heating within an upflow zone followed by (3) some change in hydrologic or geologic conditions that initiates drainage of liquid from portions of the upflow zone; and (4) low-permeability barriers that inhibit the movement of cold water into the evolving vapor-dominated zone (see Ingebritsen and Sorey, 1985).

The conditions specified at the lower boundary in simulations of Model II are less restrictive than those required for the vapor-dominated zone in Model I, which involved a high rate of conductive heat input that implied an underlying magmatic heat source. The upflow or lateral flow of thermal fluid that feeds the vapor-dominated zone in Model II can capture heat flow over a relatively large area.

The thickness of the vapor-dominated zone in Model II is controlled by the permeability structure; that is, by the depths to the caprock (fig. 2b - $k_v(2)$) and to the lateral conduit. Pressures within the vapor-dominated zone are constrained by the liquid-saturated thickness above the base of the caprock, and are also affected by any parameters that influence the rate of steam upflow from the area of phase separation.

Simulations of Model III demonstrated that the vapor-dominated zone in this model can evolve relatively rapidly without changes in rock properties or boundary conditions, given circumstances that allow for a high rate of steam upflow from the area of phase separation. The system evolves similarly to Model II. However, there is no period of drainage of liquid; the steam quality of the discharge at the land surface simply increases as the liquid saturation in the area of phase separation decreases.

Near the land surface the pressure gradient within the vapor-dominated zone in Model III is greater than hydrostatic (fig. 1), so no caprock is needed. The only requirement is that vertical permeability within the vapor-dominated zone be 1 to 2 orders of magnitude greater than the horizontal permeability into the surrounding rocks - a condition that is likely to be found in many fractured rocks.

Though the systems represented by Models II and III appear identical at the land surface, drilling in the area of steam-heated features might distinguish between the two models. Unless fluid temperatures are unusually high, the vapor-dominated zone in Model III must be relatively thin, since boiling and phase separation takes place at near-hydrostatic pressures. A thick vapor-dominated zone and/or pressures much less than local hydrostatic would suggest a system like Model II. The models might be distinguished without drilling by their response to stress. For example, the lack of a caprock in Model III implies that the steam-heated discharge will be more responsive to pressure changes at depth, such as those caused by fluid withdrawal.

Vapor-dominated conditions like those in Model III may be found locally in systems similar to Models I and II. Surface features provide evidence for vapor-dominated conduits through the condensate zones at such systems. If pressures at the top of the underlying vapor-dominated zones are near local hydrostatic, the vapor-dominated "fracture zone" in Model III is a reasonable analog for these conduits.

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