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THE EVOLUTION AND NATURAL STATE OF LARGE-SCALE VAPOR-DOMINATED ZONES

S.E. Ingebritsen

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

ABSTRACT

Numerical simulation is used to define the rather special conditions under which large-scale vapor-dominated zones can evolve. Given an adequate supply of heat, a vapor-dominated zone can evolve within low-permeability barriers without changes in rock properties or boundary conditions. However, the evolution of the system is accelerated in cases involving an initially high fluid throughflow rate that decreases with time. Near-steady-state pressures within the vapor-dominated zone are shown to vary with depth to the caprock.

INTRODUCTION

Within a hydrothermal convection system, vapor-dominated conditions may be extensive areally (to 10's of square kilometers) and vertically (more than 3 km), as at The Geysers, California, or they may be very localized, confined to a few fractures or fracture systems. This paper presents results from a series of numerical experiments designed to illustrate the evolution and natural state of large-scale vapor-dominated zones. The numerical models are used to address a number of fundamental questions about the occurrence and behavior of such zones.

A classic paper by White and others (1971) proposed a model of vapor-dominated hydrothermal systems and compared such systems with the more common liquid-dominated or hot-water type. The essence of this model is that within part of a vapor-dominated system liquid is relatively immobile and steam is the pressure-controlling phase, and that springs fed by vapor-dominated systems are low in chloride, gassy, and generally acidic. As figure 1 shows, any distinction between vapor-dominated and liquid-dominated conditions based on the vertical pressure gradient, the relative mass flux of steam and liquid (q_s/q_w) or relative permeabilities (k_{rs}/k_{rw}) is arbitrary. However, it seems reasonable to assume that natural vapor-dominated zones of the type described by White and others would fall in the lightly patterned region of figure 1. Within this region

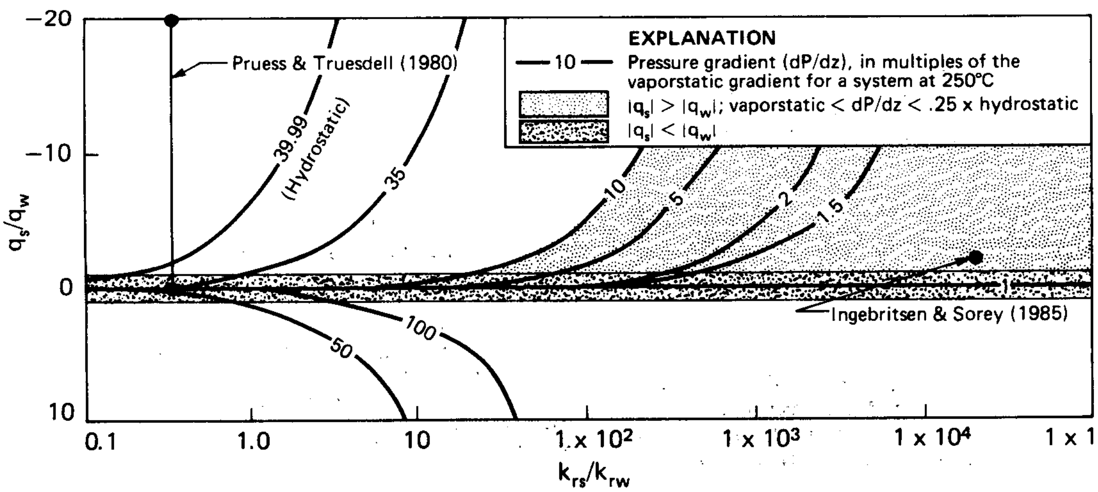

Fig. 1 Relationship between the vertical mass flux ratio of steam (q_s) to liquid (q_w) and the relative permeability ratio (k_{rs}/k_{rw}) for various vertical pressure gradients. A pressure gradient of one is vaporstatic.

there is vapor/liquid counterflow, with the vapor flux greater than the liquid flux, and the pressure gradient is less than 25 percent of hydrostatic.

The hydrothermal convection systems at The Geysers, California, Kamojang, Indonesia, and several areas (including Larderello) in Tuscany, Italy are general ly referred to as vapor-dominated systems. The Matsukawa system, Japan is sometimes included in this group. The Geysers, Kamojang, and the Tuscany systems are all characterized by extensive vapor-dominated zones with near-vaporstatic vertical pressure gradients. Because of the low pressure gradients, these vapor-dominated zones are generally underpressured with respect to local hydrostatic pressures. They are apparently shielded from surrounding flow systems by low-permeability barriers, and are overlain by a zone that is liquid saturated or nearly saturated with a mixture of steam condensate and shallow groundwater. This shallow layer is sometimes referred to as the condensate zone.

Pressures in the upper parts of the vapor-dominated zones at the Geysers, Kamojang, and Larderello are generally near 30.6 bars, the pressure of saturated steam at maximum enthalpy. Wells completed into the vapor-dominated zones at The Geysers, Kamojang, and the Tuscany systems produce saturated or slightly superheated steam and little or no water. Wells at Matsukawa also produce "dry" steam, but the pressure gradient within the reservoir is apparently closer to hydrostatic than vaporstatic (Donaldson and Grant, 1981).

PREVIOUS WORK

There has been little quantitative analysis of the physical processes controlling the evolution and natural state of vapor-dominated zones. This is largely attributable to the general lack of analytical solutions to geologically meaningful two-phase flow problems, and to the computational difficulty and expense of simulating two-phase flow problems numerically over time scales of geologic interest.

Schubert and Straus (1979, 1980; Straus and Schubert, 1981) modeled certain aspects of vapor-dominated zones analytically. However, their reliance on analytical methods limited them to one-dimensional, steady-state cases, and often required additional simplifying assumptions.

Pruess and Truesdell (1980) attempted to simulate the evolution of a vapor-dominated system numerically with a radial model involving conductive heat flow at the lower boundary (approximately 30 hfu)1/, a constant pressure/temperature condition at the upper boundary, and no-flow lateral boundaries. Their steady-state result involved a zone of two-phase counterflow beneath a 400 m thick low-permeability (3×10^{-12} cm^2) caprock. Within this two-phase zone the ratio k_{rs}/k_{rw} was approximately 0.3 and the pressure gradient was necessarily near hydrostatic (see figure 1).

Pruess and others (1983) simulated approximately 15 years of production from the vapor-dominated zone at Serrazzano, Italy. They incorporated what was known about the geology of the system into their model, but did not attempt to simulate the evolution and natural state. They also assumed that liquid was immobile within the vapor-dominated zone, and that the system was closed to recharge and discharge.

Ingebritsen and Sorey (1985; Sorey and Ingebritsen, 1984) described numerical simulations of the evolution and natural state of a "parasitic" vapor-dominated zone overlying and fed by a lateral flow of thermal water. The pressure gradient in the vapor-dominated zones in their models was near-vaporstatic (see figure 1).

Most recently, Pruess (1985) demonstrated numerically that a brief period of limited discharge through a low-permeability caprock could cause a transition from "liquid-dominated heat pipe" conditions (a slightly subhydrostatic pressure gradient and a boiling point with depth temperature distribution) to vapor-dominated conditions. With the exception of the controlled discharge event, the system was treated as closed.

CONCEPTUAL AND NUMERICAL MODELS

Figure 2 is a schematic diagram of the conceptual model that White and others (1971) developed, based largely on observations from The Geysers and Larderello. Within the extensive vapor-dominated zone in this model, the pressure gradient is somewhat above vaporstatic. Saturated steam and water coexist within the vapor-dominated zone, and there is steam/liquid counterflow, as a fraction of the steam rising through the larger channels condenses and flows down

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1/ One heat flow unit (hfu) = 41.84 mW/m^2

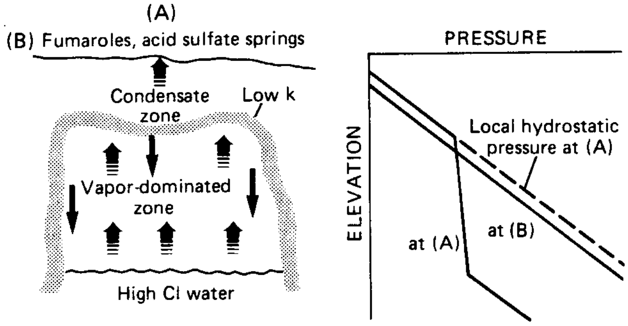

Fig. 2 Conceptual model of large-scale vapor-dominated zone with solid limited throughflow. Solid arrows for liquid, broken arrows for vapor flow.

in narrower channels and pore spaces. The vapor-dominated zone is presumably underlain by a zone of high-chloride liquid, but unlike the "parasitic" vapor-dominated zone (Ingebritsen and Sorey, 1985; Sorey and Ingebritsen, 1984) there is no evidence for significant liquid throughflow.

The low-permeability aureole surrounding the vapor-dominated zone (figure 2) may be related to deposition of silica, calcite, or gypsum, as discussed by White and others (1971); argillization, natural structural barriers, or a combination of these factors. For example at The Geysers, the main vapor-dominated reservoir is overlain by relatively impermeable caprocks consisting of serpentinite, melange, and metagraywacke (figure 3a). Argillic alteration also apparently helps to seal the top of the reservoir (Hebein, 1985). The reservoir may be bounded laterally, at least in part, by mineralization along the Mercuryville and Collayomi fault zones. At Larderello (figure 3b), steam is found mainly in antiforms within carbonate and evaporitic (dolomitic-anhydrite) rocks. The carbonates are overlain by low-permeability shales and sandstones which isolate the vapor-dominated zones both laterally and vertically. At Matsukawa (figure 3c), the Matsukawa Andesite is the caprock and the margins

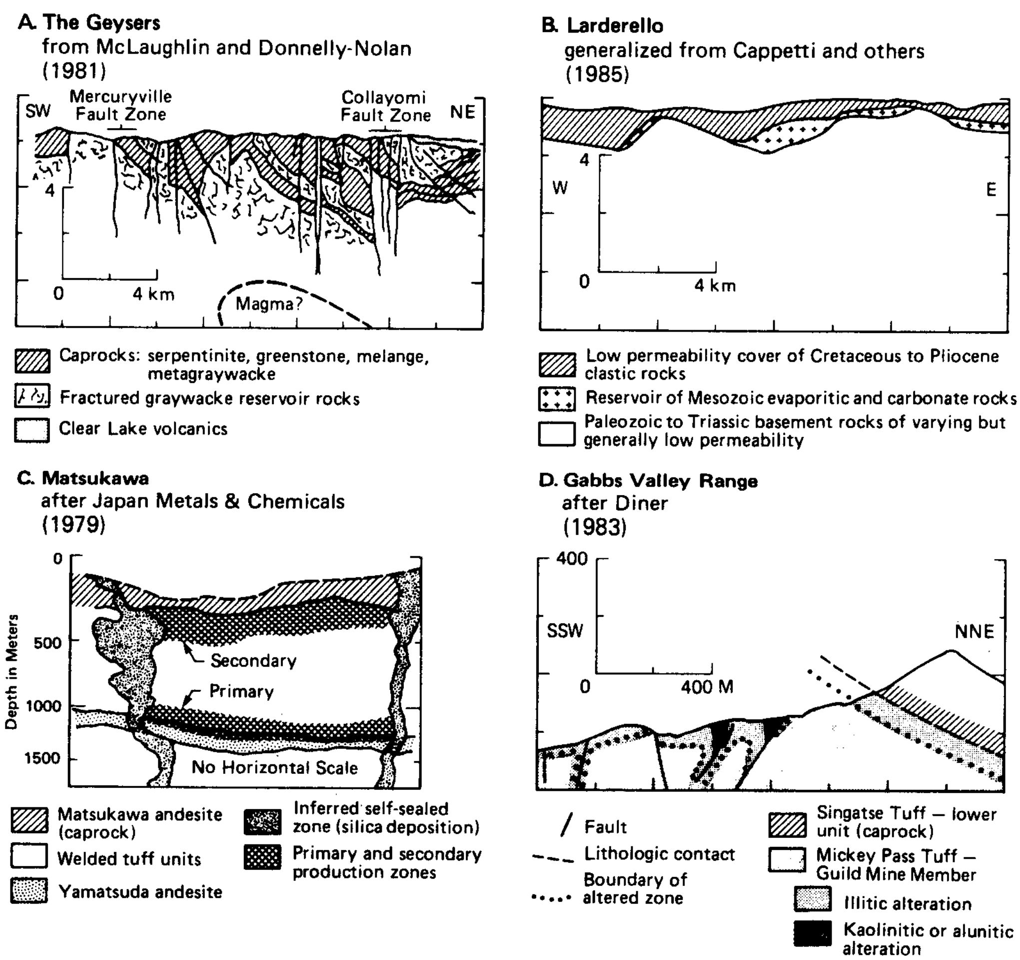

Fig. 3 Simplified geologic cross sections of various vapor-dominated systems, showing suggested low permeability boundaries to the vapor-dominated zones.

of the reservoir appear to be self-sealed by deposition of silica (M. Hanano, oral communication, 1985). At a possible fossil vapor-dominated system in the Gabbs Valley Range, Nevada (figure 3d; Diner, 1983; Stearns, 1982), the caprock was a poorly welded ash flow tuff. The pattern of mineralization suggests that fluid circulation beneath this unit was largely confined to fault zones, each of which may have comprised an isolated vapor-dominated heat pipe.

Isolation due to self-sealing - by deposition of silica due to cooling at the margins of a system, or by deposition

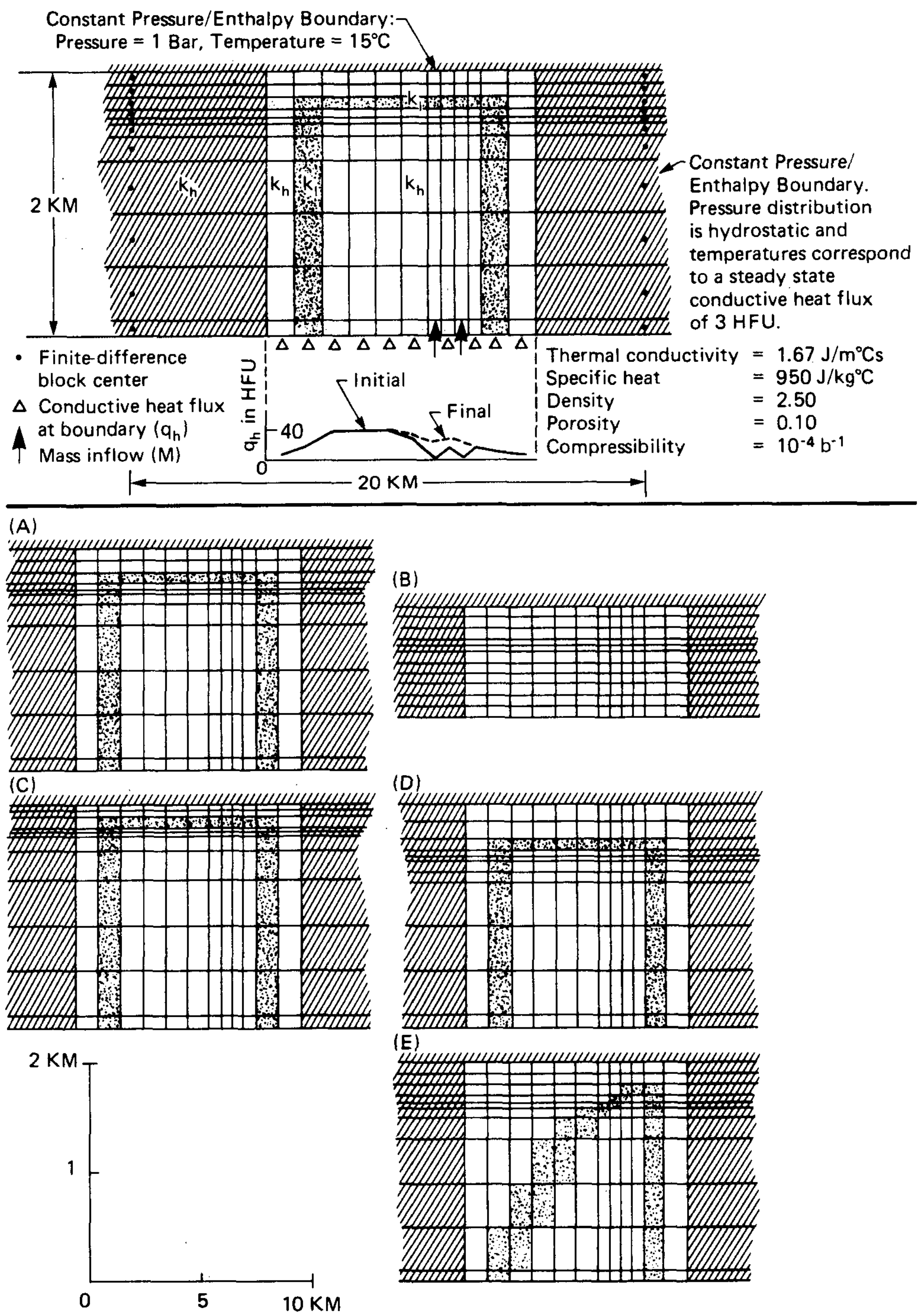

Fig. 4 Geometric models used in simulations of the conceptual model shown in figure 2.

of calcite, gypsum, or anhydrite as recharge water warms - is likely to be more effective during a liquid-dominated stage that precedes development of vapor-dominated conditions. At Reykjanes, Iceland, self-sealing by silica and calcite sustains a pressure difference of nine bars across the lateral boundaries of a high-temperature liquid-dominated system (Tomasson and Smarason, 1985).

Figure 4 shows the geometric models used to represent the conceptual model shown in figure 2 and, in a more generalized fashion, the real systems shown in figure 3. These geometric models are simplified, but adequate to represent the essential features of large-scale vapor-dominated systems. They are two-dimensional vertical cross sections, with no boundaries closed to mass or energy. The system is flanked by nonthermal groundwater systems, represented by constant pressure/enthalpy boundaries, but buffered to some extent by low-permeability zones (k_1). There is input of mass (M) and heat (q_h) (by both convection and conduction) at the base, and discharge of heat and recharge or discharge of mass at the land surface.

The computer code used to simulate heat and mass transport within these geometric models was a modified version of the three-dimensional, two-phase program described by Faust and Mercer (1979). With this program, solutions for fluid pressure and enthalpy at selected times are obtained using finite-difference techniques. Other system properties such as liquid-steam saturation and rock-fluid temperature are obtained from the calculated pressures and enthalpies. Modifications to the original code were made to improve the scheme for upstream weighting of fluid properties and to allow conductive heat flux to be specified as a boundary condition (Ingebritsen, 1983), and to extend the allowable temperature range.

RESULTS

The results presented here are abstracted from a Ph.D. dissertation in progress (Ingebritsen, 1986). The simulations discussed in this section are summarized in Table 1. Those marked with an asterisk in Table 1 led to extensive vapor-dominated zones with near-vaporstatic pressure gradients, while the others led only to short-lived (Run 3) or very localized vapor-dominated conditions (Runs 5 and 6), or did not lead to the formation of vapor-dominated zones at all. Comparison of these various results leads to a number of interesting conclusions.

Initial conditions for each simulation were a hydrostatic pressure distribution and a low-temperature conductive temperature regime. Total simulation times ranged from 10,000 to 40,000 years.

Table 1. Summary of numerical simulations discussed in the text. Runs marked with an asterisk led to extensive vapor-dominated zones.

Run	Geometry [1/]	k_h, [1/] in cm	k_1, [1/] in cm	$\bar{q}_{hf}$, [2/] in hfu	M_i, [3/] in kh/s	M_f, [4/] in kg/s	Time to M_f, in years	Total simulation time, in years
1*	A	1.0×10^{-9}	5.0×10^{-13}	27.5	100	2	3500	10,000
2*	A	1.0×10^{-9}	5.0×10^{-13}	27.5	100	2	5500	10,000
3	A	1.0×10^{-9}	5.0×10^{-13}	0	100	2	3500	10,000
4*	A	1.0×10^{-9}	5.0×10^{-13}	27.5	0	0	N.A.	40,000
5	A	1.0×10^{-9}	5.0×10^{-13}	27.5	100	5	3500	10,000
6	A	1.0×10^{-9}	5.0×10^{-13}	27.5	100	10	3500	10,000
7*	A	1.0×10^{-9}	5.0×10^{-15}	27.5	0	0	N.A.	40,000
8	A	1.0×10^{-9}	5.0×10^{-11}	27.5	100	2	5500	10,000
9	B	1.0×10^{-12}	1.0×10^{-12}	27.5	0	0	N.A.	25,000
10	B	1.0×10^{-11}	1.0×10^{-11}	27.5	0	0	N.A.	25,000
11*	C	1.0×10^{-9}	5.0×10^{-13}	27.5	100	2	3500	10,000
12*	D	1.0×10^{-9}	5.0×10^{-13}	27.5	100	2	3500	10,000
13*	E	1.0×10^{-9}	5.0×10^{-13}	27.5	100	2	3500	10,000

1/ See Figure 4.
2/ Final mean conductive heat flow at base of model.
3/ Initial mass inflow rate.
4/ Final mass inflow rate.

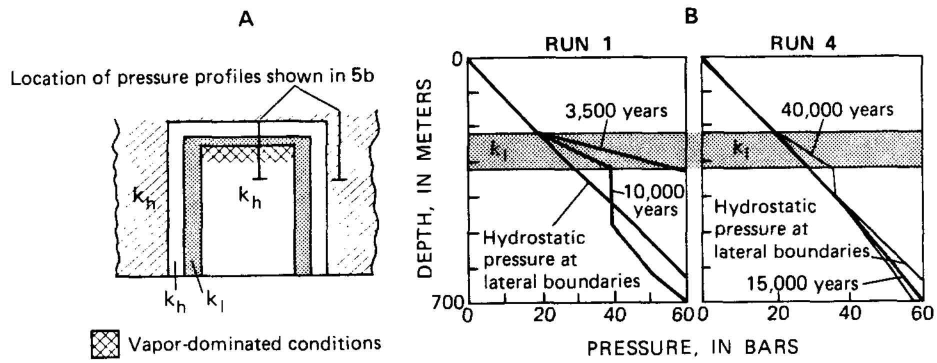

Fig. 5 (a) Extent of vapor-dominated conditions at the end of Run 1, and location of pressure profiles shown in 5b. (b) Pressure profiles at selected times during Runs 1 and 4.

These times were sufficient to allow most of the simulations to reach a near-steady-state condition.

The simulations demonstrate the feasibility of two different evolutionary pathways: a decrease in mass inflow over time (e.g. Table 1 - Run 1), and conductive heating at a constant rate with no changes in boundary conditions (e.g. Run 4). Both of these scenarios led to extensive vapor-dominated zones, although the system evolved more rapidly in runs that involved an early period of high liquid throughflow. Figure 5a shows the extent of vapor-dominated conditions for such a case (Run 1) at the total simulation time of 10,000 years. Figure 5b shows pressure profiles at selected times during this run and during a simulation that involved conductive heating only (Run 4). At later times in both cases pressures are greater than hydrostatic above the vapor-dominated zone, and the vertical pressure gradient is near-vaporstatic within the vapor-dominated zone and near-hydrostatic below the vapor-dominated zone. In both cases the pressures at the top of the vapor-dominated zone are somewhat above hydrostatic. This explains the stability of the liquid saturated layer above the vapor-dominated zone, and is related to the permeability contrast between k_l and k_h (figure 4). Superhydrostatic pressures in shallow steam zones have been reported at The Geysers (Allen and Day, 1927; up to approximately 150 percent of hydrostatic at 150 m depth), Mud Volcanoes, Yellowstone (White and others, 1971; approximately 125 percent of hydrostatic at 106 m depth), and Svartsengi, Iceland, where a "steam cap" is forming in response to exploitation (Gudmundsson and Thorhallson, 1986).

Note that the vapor-dominated zones in both cases are relatively thin (figure 5b) - much thinner than that at The Geysers, for example. At a total simulation time of 40,000 years the conduction-only run (Run 4) is far from steady state, but the run involving a decrease in mass inflow (Run 1) is approaching steady state at the total simulation time of 10,000 years. Thus the vapor-dominated zone in Run 1 may be near an equilibrium thickness. As the thickness of the vapor-dominated zone increases, the lateral pressure gradient into the vapor-dominated zone increases (figure 5b). Eventually, the amount of steam flowing vertically out of the vapor-dominated zone is balanced by lateral inflow. The factors affecting the thickness of the vapor-dominated zone at equilibrium include the rate of conductive heating at

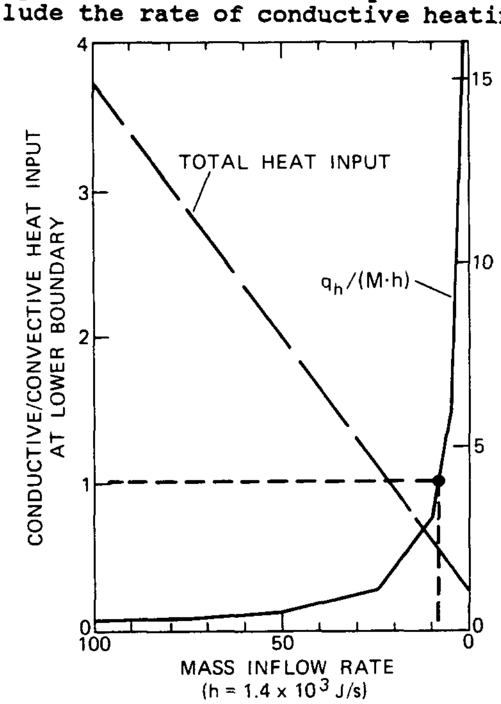

Fig. 6 Total heat input at the lower boundary of the geometric model and conductive/convective heat input ratio, both as functions of mass inflow rate M. For M < 10 kg/s, conductive heat input is greater than convective.

the base of the model and the permeability of the low-permeability barriers that inhibit lateral flow (k_1). An increase in the heat input would increase the rate of steam loss and lead to a thicker vapor-dominated zone. If the lateral barriers (k_1) were completely impermeable (preventing inflow), the vapor-dominated zone would keep growing indefinitely. Of course, if the vapor-dominated zone reached the lower boundary of the geometric model the boundary condition used would become inappropriate.

A series of simulations (Runs 4, 1, 5, and 6) illustrates the effect of varying the final rate of mass inflow M at the base of the model. The final rates range from 0-10 kg/s. Rates of 0 and 2 kg/s (Runs 4 and 1) lead to extensive vapor-dominated zones. Mass inflow rates of 5 and 10 kg/s (Runs 5 and 6) lead to higher pressures such that vapor-dominated conditions are only very localized (one to five finite-difference blocks) and pressures are above hydrostatic throughout the system. For these geometric models, this implies that the conductive heat input must exceed the convective heat input at the lower boundary (figure 6) in order for an extensive vapor-dominated zone to form.

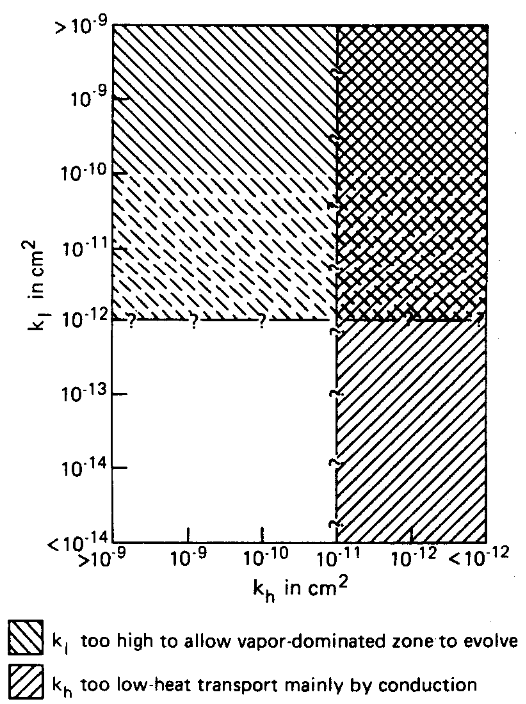

Fig. 7 Permeabilities favorable for the evolution of vapor-dominated conditions within the geometric models shown in figure 4.

The conductive heat input used in the simulations implies an underlying heat source of great intensity. Assuming no convection below the boundary, the depth to magmatic temperatures implied by the lower boundary condition is given by

$$D = K \frac{(T_m - T_b)}{\bar{q}_{hf}}$$

where K is thermal conductivity, T_m is the magmatic temperature, T_b is the temperature at the lower boundary, and $\bar{q}_{hf}$ is the average conductive heat flux at the lower boundary. The temperature at the base of the model equilibrates at about 300°C, and the average heat flow is 27.5 hfu. Assuming a magmatic temperature of 800°C and using a thermal conductivity value of 5 tcu[1/], D =.9 km. Given active convection at depths below two km (the base of the model), the calculated depth to magma would be greater. In contrast, the "parasitic" vapor-dominated zone (Ingebritsen and Sorey, 1985; Sorey and Ingebritsen, 1984) does not necessarily require such a potent local heat source, as heat can be supplied by a voluminous liquid throughflow.

Another series of simulations (Runs 1 and 7-10) shows the effect of varying the permeability distribution (figure 4: k_h versus k_1). For $k_1 \geq 10^{-12}$ cm^2, the interior of the system is insufficiently isolated from the constant pressure/enthalpy boundaries for vapor-dominated conditions to evolve. For $k_h \leq 10^{-11}$ heat transport throughout the system is dominantly conductive, so no vapor-dominated zone could evolve. (The near-isothermal conditions within the vapor-dominated zones imply convective heat flux >> conductive). This might have been anticipated by a Rayleigh number analysis of a slightly idealized version of Runs 9 ($k_h = k_1 = 10^{-12}$ cm^2) and 10 ($k_h = k_1 = 10^{-11}$ cm^2), which shows $R \sim .27$ and $R \sim 2.7$, respectively. These values are approximately equal to or below R_c for the onset of convection (Straus and Schubert, 1977). This series of simulations suggests that a permeability contrast ($k_h > k_1$) is needed to allow a vapor-dominated zone to evolve (figure 7). Straus and Schubert (1981) reached a similar conclusion. Their earlier work (Schubert and Straus, 1980) had shown that a permeability of 4 x 10^{-13} cm^2 or less was required for gravitational stability of water over steam. In their later work (1981), they found that higher permeabilities were needed within the vapor-dominated zone itself, and, thus, recognized the need for a permeabi-

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1/ One thermal conductivity unit (tcu) = 418.4 mW/m-°k

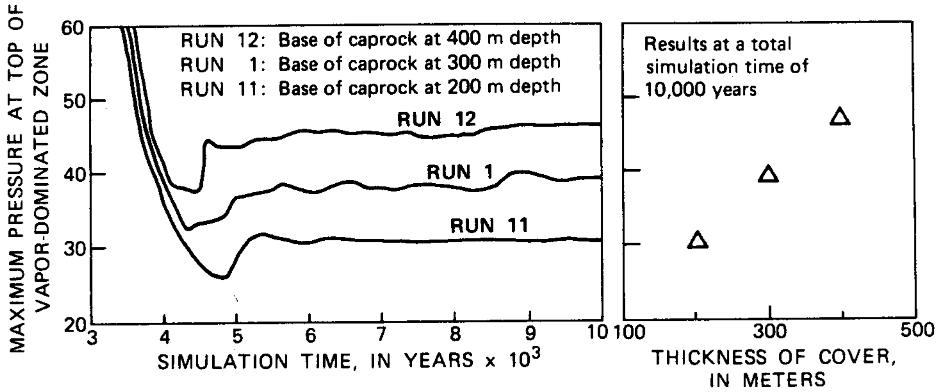

Fig. 8 Pressure at the top of the vapor-dominated zone as a function of time in runs that involve different depths to the caprock, and near-steady-state pressures as a function of thickness of cover.

lity contrast at the top of the vapor-dominated zone.

Near-steady-state pressures within the vapor-dominated zone vary regularly in response to changes in the depth to the low permeability caprock (figure 8; Runs 1, 11, 12). This is predictable, for in order to sustain a flux of steam into the base of the caprock, pressures at the top of the vapor-dominated zone must exceed the overlying weight of water. Pressures within the vapor-dominated zone are also sensitive to the geometry of the caprock (Run 13 - not shown).

The minimum rate of heat loss from a vapor-dominated zone at various depths or

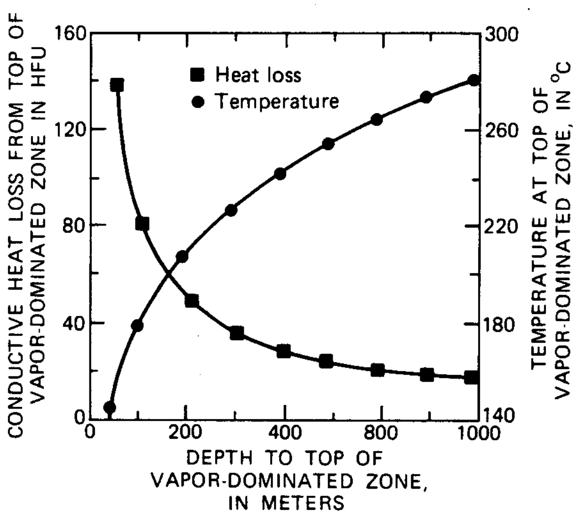

Fig. 9 Minimum heat input rates necessary for evolution of a vapor-dominated zone at various depths. Conditions at the top of the vapor-dominated zone are assumed to fall on the boiling point with depth curve.

pressures can be estimated by assuming that the heat loss is largely by conduction to the land surface, that the temperature at the top of the vapor-dominated zone lies on the boiling point with depth curve, and that K = 5 tcu (figure 9). An equivalent rate of heat input could be the minimum required to sustain the vapor-dominated zone. Somewhat surprisingly, this analysis suggests that a deeper/higher pressure vapor-dominated zone might require a less intense heat source.

Several of the simulations led to vapor-dominated zone pressures greatly in excess of the pressure of maximum enthalpy of saturated steam. Field evidence for such high pressures is scarce. However, Stefanssson (1985) has suggested vapor-dominated conditions at a pressure of 84 bars at the Nesjavellir high-temperature field, Iceland. Dry steam entries at pressures of 40 bars (in shallow horizons; Celati and others, 1978) to 70 bars (in deeper horizons; Cappetti and others, 1985) have been reported at Larderello, and pressures of around 60 bars have been reported in both shallow and deep horizons at Travale, Tuscany (Cappetti and others, 1985). However, there are not enough pressure measurements in any of these cases to show whether the pressure profile is near vaporstatic. Since the rate of heat loss from such deep/high pressure vapor-dominated zones is relatively small (figure 9), they might be encountered near the margins of known vapor-dominated systems or on the flanks of intense heat flow anomalies, rather than at the centers of such anomalies.

These experiments show that the pressure of maximum enthalpy of saturated steam does not control pressures in large-scale vapor-dominated zones. An alternate explanation is needed for the coincidence of several known systems at pressures of 30-35 bars.

SUMMARY

Given an adequate supply of heat, a large-scale vapor-dominated zone can evolve within low-permeability barriers without changes in boundary conditions or rock properties. However, the evolution of the system is accelerated in cases involving an initially high fluid throughflow rate that decreases through time. The conductive/convective heat flow ratio at the lower boundary of the system must be >>1, because the low permeability aureole surrounding the vapor-dominated zone and the near-vaporstatic pressure gradient within the vapor-dominated zone preclude high throughflow rates.

Although low permeability barriers are necessary to buffer the vapor-dominated zone from surrounding and overlying zones with near-hydrostatic pressure gradients, permeability within the vapor-dominated zone itself must be relatively high, since vertical heat transport is dominantly by a heat-pipe mechanism rather than conduction. Thus, vapor-dominated zones cannot exist in a medium of uniform low permeability - some permeability contrast is necessary. Given low permeability barriers with permeability/thickness ratios low enough to allow a vapor-dominated zone to evolve, the system is relatively insensitive to the permeability of surrounding and overlying normally-pressured flow systems. Heat transfer in these zones may be dominantly convective or conductive. The stability of a liquid saturated zone overlying the vapor dominated zone is readily explained by pressures at the top of the vapor-dominated zone that are somewhat in excess of local hydrostatic pressures.

Near-steady-state pressures within the vapor dominated zone are not controlled by the pressure of maximum enthalpy of saturated steam (30.6 bars). They are shown to vary regularly with depth to the caprock (i.e., thickness of cover). The coincidence of a number of systems at pressures near the pressure of maximum enthalpy of saturated steam is yet to be explained.

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