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Vapor Pressure Lowering in Brines and Implications for Formation of a High Temperature Reservoir

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Introduction

That a "high temperature reservoir" (HTR) underlies a "typical" vapor-dominated reservoir under certain circumstances is well known (Drenick, 1986; Pruess et al., 1987; Walters et al., 1988). However, formation and behavior of such a feature is poorly understood. Recent theories regarding the behavior of the HTR fall into one of two broad categories: transient and steady state. In the transient models (e.g., Drenick, 1986; Walters et al., 1988; Truesdell, 1991), the HTR is a component of the typical vapor-dominated reservoir for a relatively short period of time.. These models generally assume either a recent boiling of a liquid system (a fossil liquid system; Drenick, 1986; Walters et al., 1988), or downward extension of the "typical" reservoir into hot dry rock (Truesdell, 1991). Steady state models (Shook, 1993a; Lai et al., 1994) consider the HTR as a steady component of the geothermal reservoir. As in the case of the transient theories, several different explanations are given for the formation of the HTR. For example, Shook (1993a) used vapor pressure lowering in a fractured domain to develop an HTR, whereas Lai et al. (1994) used non-uniform heating in a porous media in forming the HTR.

While any of these theories may indeed explain the formation of the HTR, perhaps the most significant implication of the differences is the variation in liquid saturation of the HTR. For example, the Lai et al. (1994) steady state model exists only at very low liquid saturations overall, and superheated conditions in the HTR. Shook (1993a), on the other hand, showed large liquid saturations in the HTR. Such differences in saturation have potentially large effects on hypothesized response to exploitation. It would seem, then, that additional physics and field observations must be incorporated in these models to better constrain the problem and converge upon the correct mechanism.

Recent studies may provide additional clues regarding development of the HTR at The Geysers. On the basis of fluid inclusion work, Moore (1992) suggests the presence of very saline brine (up to 40 wt % NaCl) in the HTR, with much lower salinities in the "typical" reservoir. Moore further suggests that low permeabilities within the HTR may be responsible for the salinity contrasts. However, at this time it is not known whether these fluid inclusion results apply to the current hydrothermal cycle of the reservoir.

Williams et al. (1993) presented heat flow studies of Northwest Geysers, and showed a thermal transient in the caprock in the northwest portion of the field that is not found to the southeast. On the basis of some one-dimensional heat conduction calculations, they conclude that this thermal transient may be caused by a temperature reduction of 40°C 5,000-10,000 years ago in the northwest portion of the field. A second possibility not considered by these authors is that a thermal perturbation occurred to the southeast, and that the thermal transient has already been attenuated nearer the source. From their figure 9, this would place the perturbation temporally about 20,000 years ago.

This paper summarizes some preliminary numerical simulations of the formation of a HTR. The numerical model TETRAD (Vinsome, 1991; Vinsome and Shook, 1993) was used in the study. A two-dimensional model was used, and a possible evolutionary scenario for The Geysers was simulated. Results of the study indicate that a HTR may form under a variety of conditions, and may either be two-phase or superheated. Using brine as the reservoir fluid tends to create a two-phase HTR, with a substantial concentration of salt in that zone. The HTR developed in this study appears to be transient in nature, but is cooling only very slowly.

Reservoir Description

The reservoir model used in this study is a two-dimensional cross section of a fractured media. The Warren and Root (1963) model was used, with some matrix-matrix interactions allowed both vertically and horizontally. Dimensions of the domain are 400 m by 100 m areally, and 1200 m vertically. Fracture spacing was taken as 100 m.Petrophysical properties for the reservoir were taken from the literature, and are representative of Geysers rock. Fracture porosity and permeability were taken as 0.01 and 10^{-14} m^2 (10 md), respectively. Matrix properties used were $\varphi = 0.04$ and $k = 10^{-17}$ m^2 (10 μd). These properties were constant throughout the domain, except as noted below.

Relative permeability and capillary pressure curves are not available in the literature. The parametric curves used are given in Table 1. Endpoint relative permeabilities and curvatures for both permeability and capillary pressure differ from fracture to matrix, as summarized in the table. An arbitrarily large maximum capillary pressure of 40000 kPa (400 bars) at standard conditions was used for both fractures and matrix. Capillary pressures are scaled as a function of temperature and as functions of permeability and porosity as described by Shook (1993b). Maximum capillary pressure at initial reservoir temperature is approximately 12,250 kPa (122.5 bar). Petrophysical properties are summarized in Table 1.

The modifications to the petrophysical properties noted above involve permeability and porosity at depth. Several authors have noted variations in permeability and porosity with depth (Gunderson, 1990; Williamson, 1989). Additional evidence presented by Sternfeld (1989) indicates a facies change at depth in the northwest portion of the field. To mimic this facies change, decreases in permeability and porosity in the rock matrix, and reduction of fracture porosity were made. This "facies change" is not uniform across the domain. Instead, it is relatively thick on one side, and pinches out toward the center of the domain. No attempt was made to invoke a gradual change in facies, but rather an abrupt in properties was made. In this portion of the domain, $k = 10^{-19}$ m^2 (0.1 μd) in the matrix, and $\varphi = 0.005$ for both fracture and rock matrix. The reservoir is depicted schematically in Figure 1.

Model Description

The model was initially assumed to be in hydrostatic equilibrium and at an initial temperature of 240°C. Pressure at the top of the reservoir was 3600 kPa, slightly above the saturation pressure of pure water. The reservoir fluid was a low-concentration brine, with a salt concentration of 3 wt %. Relative vapor pressure from osmotic effects for this salt concentration is approximately 0.95.

The model scenario follows that of Shook (1993a). A uniform heat flux of 0.5 W/m^2 was applied to the bottom of the reservoir, and the top of the reservoir was initially held at constant temperature and pressure. After 2000 years of equilibration, the system was perturbed by a sudden venting episode. The vent (simulated via a well) was open to the atmosphere for 60 years, and the vent rate constrained to less than 1.2 kg/s. After the vent episode, the reservoir was again allowed to equilibrate. The constant pressure/temperature boundary at the reservoir top was removed, and heat escapes the domain via conduction through the caprock.

Results from the base case simulation at t=20,000 years (18,000 yrs. after venting) are shown in Figures 2-4. The pressure profile shown in Figure 2 clearly shows vapor-dominant conditions throughout the domain. However, Figure 3 shows the presence of a high-temperature zone at depth opposite the vent. One significant feature of this simulated HTR is its non-uniform depth. The top of the HTR largely follows the "facies change" input, and therefore moves deeper toward the middle of the domain. As seen in Figure 4, the HTR is two-phase, with an average matrix liquid saturation of 0.4.

Although not shown on the figures, another interesting feature of the HTR is the chemical composition of the fluid. The initial salt content in this simulation was a uniform 3 wt. %. However, after the venting and subsequent re-equilibration, most of the salt remaining in the system is concentrated within the HTR. Simulated salt concentrations in the "typical" reservoir are less than 0.05 wt. %, whereas in the HTR concentrations vary from 20 to in excess of 40 wt %.

The time simulated was 50,000 years, or 48,000 years past the venting episode. Throughout the simulation, temperatures in the HTR changed, falling approximately 16°C in 45,000 years. Liquid saturations in the rock matrix increase modestly over the same time period. However, liquid saturations in the fractures in the HTR fluctuate over the entire simulation, with a period of several thousand years. Two distinct endpoints are observed: a "dry" cycle, where only a small mobile liquid phase is present, and a "wet" cycle, in which liquid saturations are about 30%. It is not clear at present if these fluctuations are a result of the boundary conditions or discretization scheme used, or if it is a valid cyclic response to the dynamic nature of the heat pipe.

In summary, the base case simulation displays several unique features typically associated with the HTR found at The Geysers. Its lack of uniform depth, in particular, indicates that a discontinuous facies change may be partially responsible for its development. Relatively large concentrations of salt provide the vapor-pressure lowering mechanism to allow liquid to exist in the HTR rock matrix. A cyclic pattern of liquid saturations in the fractures has been observed; however, it is not currently known whether this is a numerical artifact or a physical response of the system. Finally, changes is the thermodynamic properties of the HTR indicate that it is a transient feature, with temperature changes of about 0.33°C/1000 yrs.

Sensitivity Studies

A limited set of sensitivity studies have been conducted to determine HTR formation sensitivity to several of the input parameters. Mass fraction vented, salt content, and petrophysical properties of the HTR were varied in these simulations. In each of the following cases, a single change was made to the base case conditions.

When the vented fraction of mass in place was reduced to 35% (from about 50%), properties of the HTR changed accordingly. In this case, the HTR was liquid-dominated, with pressures and temperatures following a hydrostatic gradient and boiling with depth curve, and the top of the HTR is at a constant depth. This result appears similar to that of Lai et al. (1994) for low vapor saturations.

When salt is removed from the reservoir fluid, the character of the HTR is changed. The HTR forms with a non-uniform surface, as in the base case. In this case, however, the HTR is superheated. However, very little salt is required to develop a saturated HTR. For example, when the salt content was reduced to 1.6 wt. %, the HTR forms as observed in the base case, and again is saturated. Despite the reduced mass of salt initially present, concentrations in the HTR approach 30% by weight.

In both of these cases the HTR is much more transient in nature. For example, when no salt is present, the HTR disappears in about 30,000 years, and the entire model is a "typical" vapor-dominated reservoir, with very low liquid saturations..

A final case considered changes in both permeability and porosity in the fractured domain of the HTR. In this case, fracture permeability was reduced to 10^{-19} m^2 (0.1 μd), the same as in the matrix in the HTR. As in the base case, the HTR forms with a non-uniform surface, and similar temperature profiles are also observed. However, in this case, the pressure gradient is approximately 1 kPa/m, somewhat larger than has been reported in the literature. The liquid saturation in the HTR is larger in this case as well, with fracture liquid saturations approaching 60% and matrix liquid saturation in excess of 80%.

Conclusions

A numerical study that considers the formation and long-term behavior under pre-exploitation conditions has been conducted. Results from this study indicate the HTR may form under a variety of conditions, but salt in the reservoir fluid tends to cause the HTR to be two-phase. Including a "facies change" in the reservoir model can in certain cases lead to the development of an HTR with a variable surface depth. This lack of uniform depth and large salt concentrations, in particular, show an interesting agreement between numerical results and field observations.

Several points in this study still need to be resolved. First, the cyclic variations in liquid saturation in the HTR fractures must be better understood. Also, abrupt changes in reservoir properties were assumed for the HTR. Additional studies are planned to examine the effect of gradational changes on HTR formation. Finally, two-dimensional heat flow in the caprock will be considered in an effort to better constrain the possible timing and location of the simulated venting episode.

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Table 1: Petrophysical Properties and Initial Conditions

Petrophysical Properties	Matrix	Fractures
Porosity	0.04	0.01
Permeability (md)	0.01	10.
Relative Permeabilities		
$k_{rl} = k_{rl}^{o}\,(S)^{e_l}$	$k_{rl}^{o} = k_{rv}^{o} = 1$	$k_{rl}^{o} = k_{rv}^{o} = 1$
$k_{rv} = k_{rv}^{o}\,(1 - S)^{e_v}$	$e_l = 4.;\ e_v = 2.5$	$e_l = 2.;\ e_v = 1.5$
$S = \dfrac{S_l - S_{lr}}{1 - S_{lr} - S_{vr}}$	$S_{lr} = 0.4;\ S_{vr} = 0.05$	$S_{lr} = 0.05;\ S_{vr} = 0$

Rock Heat Capacity = 1. kJ/kg
Rock Density = 2650 kg/m^3
Rock Thermal Conductivity = 2.1 W/m°C
Matrix Block Size = 100. m
Heat Flux = 0.5 W/m^2

Initial Conditions
Pressure = Hydrostatic Gradient, P_{avg} = 7960 kPa
Temperature = 240° C
Salt Concentration = 3. wt. %

Grid Data

Nx = 4	Ny = 1	Nz = 24
Dx = 100 m	Dy = 100 m	Dz = 50 m

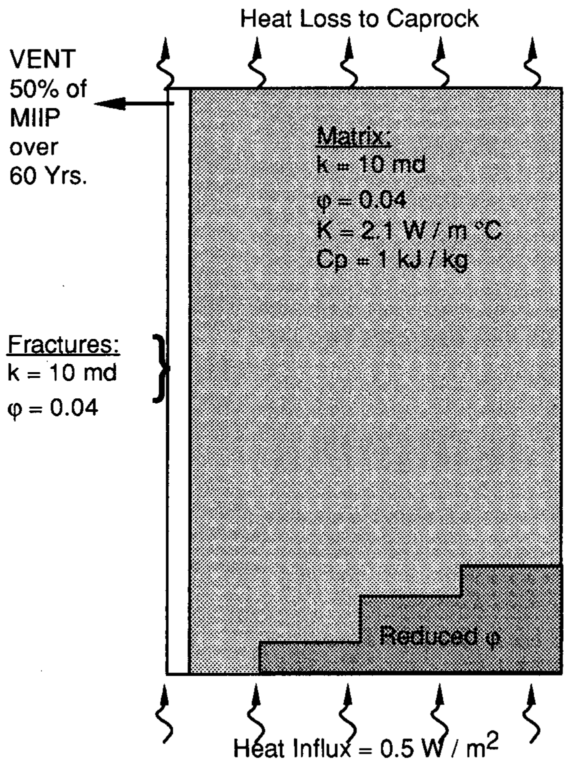

Figure 1. A schematic of the reservoir model.

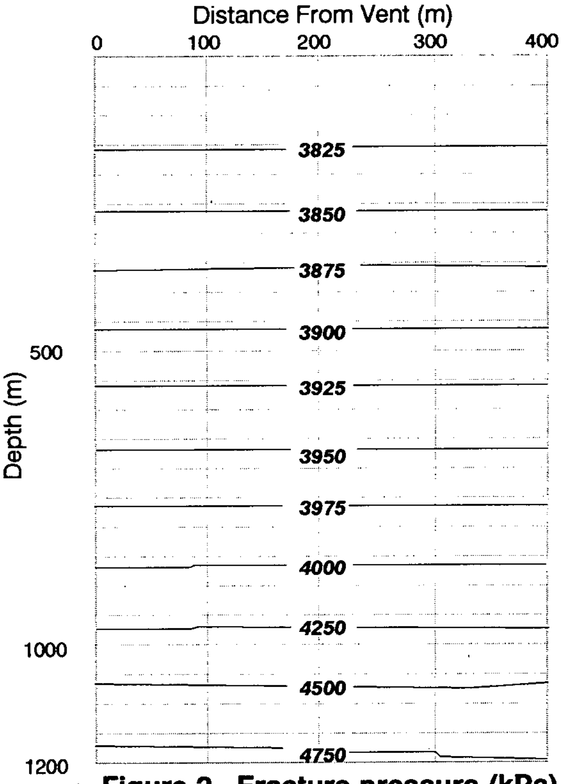

Figure 2. Fracture pressure (kPa) profile at t=20,000 years

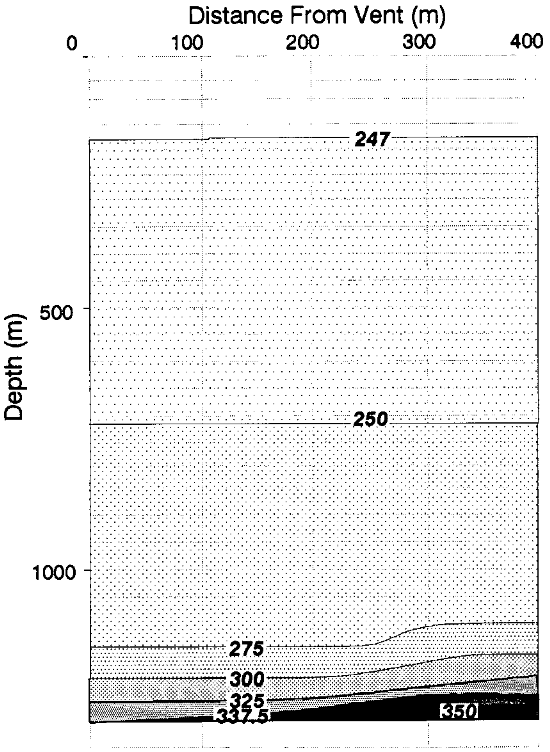

Figure 3. Fracture temperature (°C) profile at t=20,000 years

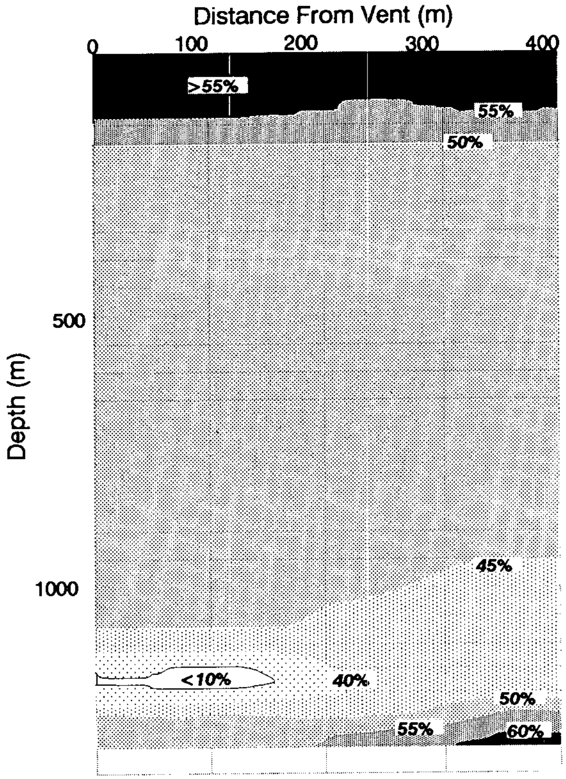

Figure 4. Matrix liquid saturation profile at t=20,000 years